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GREENHOUSE EFFECT AND GLOBAL CLIMATE CHANGE

HEARING

BEFORE THE

COMMITTEE ON ENERGY AND NATURAL RESOURCES UNITED STATES SENATE

ONE HUNDREDTH CONGRESS

FIRST SESSION

ON THE

GREENHOUSE EFFECT AND GLOBAL CLIMATE CHANGE

JUNE 23, 1988

PART 2

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GREENHOUSE EFFECT AND GLOBAL CLIMATE CHANGE

THURSDAY, JUNE 23, 1988

U.S. SENATE,
COMMITTEE ON ENERGY AND NATURAL RESOURCES,
Washington, DC.

The committee met, pursuant to notice, at 2:10 p.m., in room SD-366, Dirksen Senate Office Building, Hon. J. Bennett Johnston, chairman, presiding.

OPENING STATEMENT OF HON. J. BENNETT JOHNSTON, U.S. SENATOR FROM LOUISIANA

The CHAIRMAN. The hearing will come to order.

Last November, we had introductory hearings on the question of global warming and the greenhouse effect. We listened with mixtures of disbelief and concern as Dr. Manabe told us that the expected result of the greenhouse effect was going to be a drying of the southeast and midwest. Today as we experience 101° temperatures in Washington, DC, and the soil moisture across the midwest is ruining the soybean crops, the corn crops, the cotton crops, when we're having emergency meetings of the Members of the Congress in order to figure out how to deal with this emergency, then the words of Dr. Manabe and other witnesses who told us about the greenhouse effect are becoming not just concern, but alarm.

We have only one planet. If we screw it up, we have no place else to go. The possibility, indeed, the fact of our mistreating this planet by burning too much fossil fuels and putting too much CO_2 in the atmosphere and thereby causing this greenhouse effect is now a major concern of Members of the Congress and of people everywhere in this country.

The question is what do you do about it. Well, the first thing you do about it is learn about it, what is happening, why is it happening, how serious is the problem. Then we must begin to address this very serious problem. The leader in this problem on this committee has been Senator Tim Wirth from Colorado. Working with him, we have included some $3 million in the energy and water appropriation bill to begin our studies, and it is in this committee where the lead investigations and hearings will be held.

It is safe to say that this problem is not going to go away. It is not like a stock market crash which corrects itself in a matter of weeks or months. The problem is going to only get worse. It is not going to be easily correctable, and once we begin to find the solutions, we know those solutions are going to be both expensive as we find alternate fuels and are going to involve massive international efforts.

So, as we begin today, we are doing so with a consciousness that this is not some esoteric study of little interest to the ordinary citizen of the United States. This is not some economic study on somebody's theory. The greenhouse effect has ripened beyond theory now. We know it is fact. What we don't know is how quickly it will come upon us as an emergency fact, how quickly it will ripen from just simply a matter of deep concern to a matter of severe emergency. And what we don't know about it is how we're going to deal with it and how we're going to get the American people to understand that perhaps this drought which we have today is not just an accidental drought, not just the kind of periodic drought which we have from time to time but is, in fact, the result of what man is doing to this planet.

So, with that, I would like to turn the Chair over to Senator Wirth who will be chairing these hearings and leading our committee on the subject of global warming. And I turn the Chair over to him with our thanks for his leadership in this area.

[The prepared statement of Senator Johnston follows:]

STATEMENT OF THE HONORABLE J. BENNETT JOHNSTON

JUNE 23, 1988

I am pleased to welcome you to this afternoon's hearing on the Greenhouse Effect and policies for controlling global climate change.

Testimony presented last November, in hearings befor tHis Committee, contained sobering predictions regarding the degree and pace of global warming. Today's Greenhouse hearings will elaborate on two particularly striking facts; the first is the rapidity with which the problem of global climate change is entering the public and political consciousness; and the second is the dramatic decrease in projected time before the effects of climate change, sea level rise, and habitat degradation begin to be felt.

The current drought situation teaches us how important climate is to the nation's social, economic, and physical well being. The United States is currently mobilizing its political and financial resources to grapple with the enormous agricultural devastation of the present dry spell over the midwest and southeast portions of the United States. The present drought graphically illustrates only a small portion of the scenario which could transpire if global warming and climate change predictions are accurate.

Taking the proper steps to control the degree and pace of global warming will not be easy. The policy choices that will need to be made involve critical political and economic decisions. These hearings should spur us to once again examine the strong links between energy policy and the greenhouse effect. The burning of fossil fuels is a major contributor to the greenhouse effect. However, no one believes that we can end our dependence on these fuels overnight.

Nevertheless, the United States must make a concerted effort to increase its use of energy sources that emit relatively less carbon dioxide and other trace gases. We must revive our nuclear industry by developing a new generation of passively safe, economical nuclear reactors. We must push even harder to adopt commercially available energy efficiency measures and we must generously fund more research and development efforts in this area. We must also proceed with research that can lead to cost breakthroughs in fusion, solar, and other renewable energy sources.

We must remember also, that the greenhouse effect is implicitly linked to resource and environmental policy. The Montreal Protocol on CFC emissions is an encouraging sign that we are working in the right direction -- we must take all possible measures to ensure that this unprecedented agreement is a success. Steps are already underway in the Senate to encourage the United State to work toward strengthening the Protocol's phase-out of chlorofluorocarbons. Some have called for a similar Protocol to address the potentially more serious issue of global climate change and warming. However, it is clear that an international agreement to control CO2 and trace gas emissions will be even more problematic.

I am looking forward to today's hearings to provide some insight into the formidable task the Committee and, in fact, the nation, must face. I hope to use today's testimony as a focus for the discussion of a Congressional agenda that addresses near-term global change policy options.

STATEMENT OF HON. TIMOTHY E. WIRTH, U.S. SENATOR FROM COLORADO

Senator WIRTH [presiding]. Thank you very much. We greatly appreciate your farsighted direction of the committee dating back a long way when we first began to think about this, the hearings that were held, and also your great help in assisting in getting funding in this current appropriations cycle that I think will do a lot to not only help the research that is going on, the collection of the data that has to be done, the standardization of that data, and beginning to get that information out to a variety of communities in the country. We thank you very much for giving me this opportunity.

In the last week many of us have been seeing firsthand the effects of the drought that is occurring across the heart of the country. Meteorologists are already recording this as the worst drought we have experienced since the Dust Bowl days of the 1930's. The most productive soils and some of the mightiest rivers on earth are literally drying up. Let me cite just a few examples. Already more than 50 percent of the northern plains' wheat, barley and oats have been destroyed, and the situation could get much worse. On Tuesday, the Mississippi River sank to its lowest point since at least 1872 when the U.S. Navy first began measurements. And in my home State of Colorado, peak flows are among the lowest on record, and reservoir levels are also alarmingly low.

We must begin to ask is this a harbinger of things to come. Is this the first greenhouse stamp to leave its impression on our fragile global environment? I understand that Dr. Hansen will provide testimony this afternoon that points clearly in that direction.

The scientific community has done an outstanding job of compiling and analyzing mountains of evidence about global climate change. As I read it, the scientific evidence is compelling. The global climate is changing as the earth's atmosphere gets warmer. Now the Congress must begin to consider how we are going to slow or halt that warming trend, and how we're going to cope with the changes that may already be inevitable.

In essence, this is an issue that has moved from the world of science to the policy arena in the United States and throughout the world. All of us must begin to face up to the fact that if we continue emitting vast quantities of the greenhouse gases, we're going to face a global temperature rise larger than anything experienced in human history.

The purpose of today's hearings is to examine more closely the prospects of a warmer world and the implications of such a world for public policy. And as the drought conditions have clearly demonstrated, those considerations stretch across the public policy spectrum. The Energy Committee must move aggressively to examine how energy policy has contributed to the greenhouse effect and the kinds of changes in energy policy that may be needed to reverse the trend of increased emissions of carbon dioxide, a key byproduct of the burning of fossil fuels.

I hope that today's outstanding witnesses will join the committee in this process, and I know that we can count on your counsel in the future. Today we have some of the finest researchers on the issue of climatic change, but before introducing them, let me ask my colleagues if they have opening remarks that they might like to make.

[The prepared statement of Senator Wirth follows:]

Senator Tim Wirth

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THURSDAY, JUNE 23, 1988
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STATEMENT OF THE HONORABLE TIMOTHY E. WIRTH

JUNE 23, 1988

I want to begin by thanking the Chairman of the Energy and Natural Resources Committee, Senator Johnston, for his leadership on the issue before the Committee today, global warming and the so-called "greenhouse effect." Senator Johnston's assistance in convening this hearing, and the two days of hearings I chaired last fall, has been instrumental in focusing this Committee's attention on these profoundly important issues. I also would like to welcome Senator Chafee and Senator Baucus, who have consistently demonstrated their leadership in the effort to protect the global environment.

In the past week, many of us have been seeing first-hand the effects of the drought that is occurring across the heart of this country. Meterologists already are recoding this as the worst drought this nation has experienced since the Dust Bowl days of the 1930s. The most productive soils and some of the mightiest rivers on earth are literally drying up. Let me just cite several examples. Already, more than 50 per cent of the Northern Plains' wheat, barley, and oats have been destroyed and the situation could get much worse. On Tuesday, the Mississippi River sank to its lowest point since at least 1872, when the U.S. Navy first began measurements. And in my home state of Colorado, peak flows are among the lowest on record and reservoir levels are alarmingly low.

MORE

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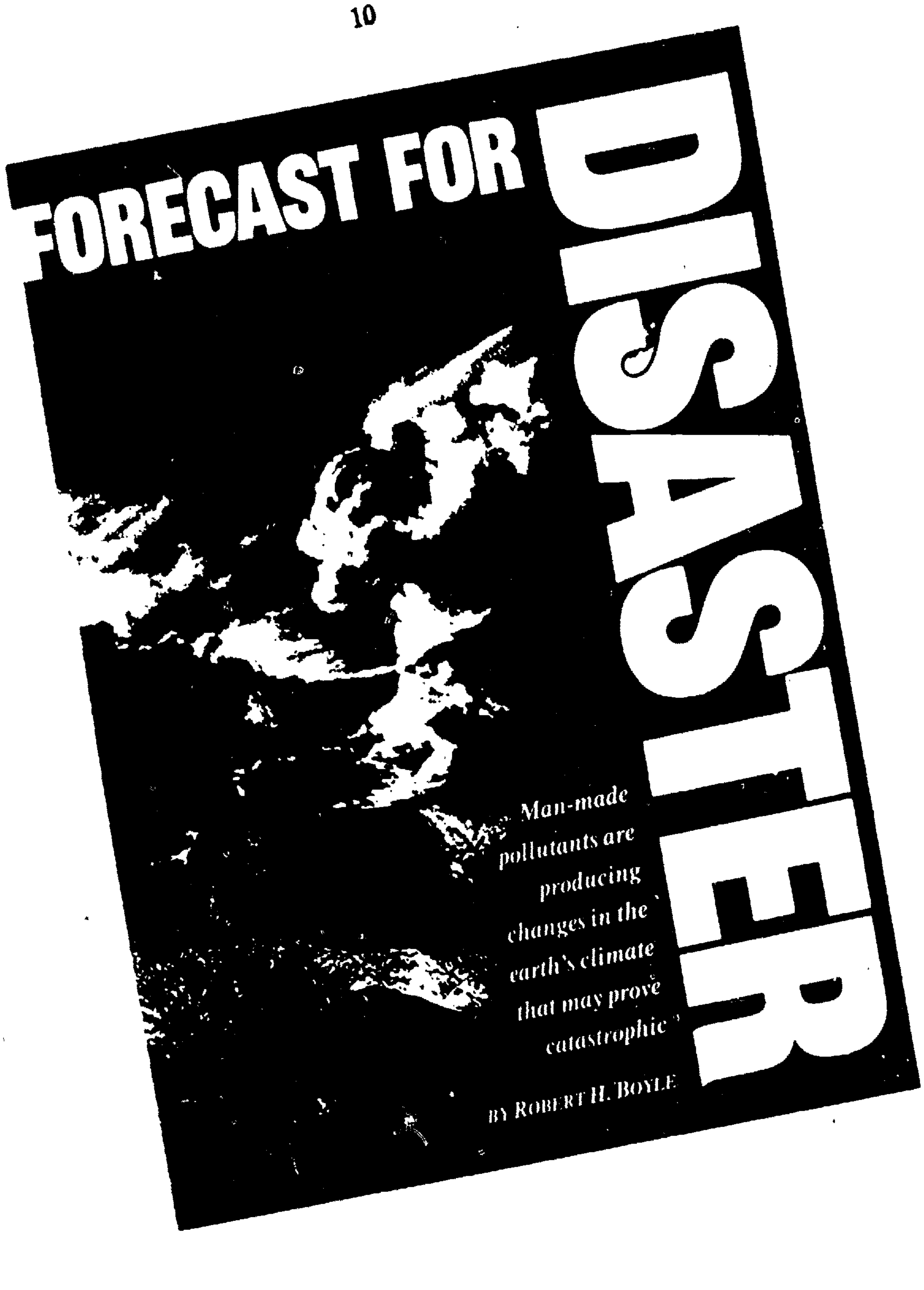
MORE

I hope that today's outstanding witnesses will join the committee in this process and that we can count on their counsel again in the future. Today, we have with us some of the nation's finest researchers on the issue of climatic change. Michael Oppenheimer, Senior Scientist at the Environmental Defense Fund and George Woodwell, Director of the Wood's Hole Research Institute, two of the three American participants and major contributors to the report we are examining today from the Beijer Institute.

James Hansen, Director of the Goddard Institute for Space Studies, whose climate data have shown that four of the warmest years on record have occurred during this decade. Dr. Syukuro Manabe from the National Oceanic and Atmospheric Administration and Daniel Dudek of the Environmental Defense Fund, both of whom have done extensive work on the implications of climate change for agricultural patterns. And Bill Moomaw of the World Resources Institute, who has done extensive work on the public policy responses that should be considered to address this problem. We thank you all for coming.

# # #



FORECAST FOR DISASTER

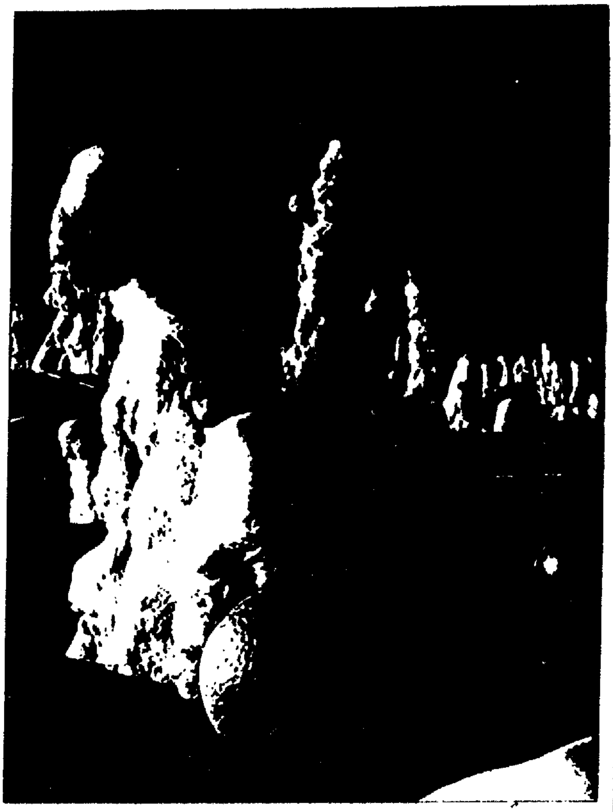
Man-made pollutants are producing changes in the earth's climate that may prove catastrophic

BY ROBERT H. BOYLE

11

And now the news for July 4, 2030

- *The second hurricane of the year has struck the East Coast. The 15-foot seawalls built to protect Baltimore, Philadelphia, New York and Boston held against 12-foot tides, but a 25-foot storm surge swept over the eastern tip of Long Island, drowning 260 residents who had refused to leave their homes despite a federal evacuation order. The toll of dead on Martha's Vineyard, Nantucket and Cape Cod is estimated at 50. The 310 fatalities are still far fewer than the 5,600 people who drowned in last month's hurricane in south Florida.*
- *Twenty-two inches of rain from the hurricane flooded Washington, D.C., breaking the heat wave that had gripped the city for 62 straight days of 90-plus temperatures. This fell short of the record set eight years ago when 72 consecutive 90-plus days caused the move of the nation's capital to the cooler environs of Marquette, Mich.*
- *In Sepulveda, Calif., neighbors hammered an elderly widow to death when they learned she had been secretly watering a pot of geraniums. A footnote to this grim story: The woman's husband had died of thirst during the California drought of 1998.*
- *Food riots broke out in France, where vineyards and farmlands have turned arid amid the rising temperatures.*
- *Dust bowl conditions continue in the Plains States of the U.S., but orange production is up in Saskatchewan. In eastern Siberia the outlook for a good cotton harvest is promising.*
- *In Stowe, Vt., botanists announced the death of the last red spruce. The species' demise is blamed on a combination of stresses: acid rain, global warming and ultraviolet radiation.*
- *In baseball, the Anchorage Braves beat the New York Mets 5-3. In Los Angeles, the Dodgers' game against the Calgary Giants, scheduled for the usual 5:30 a.m. start, was postponed because of dust storms.*
- *And now the weather. After leaving a swath of destruction in its wake along the East Coast, Hurricane Bruce is expected to move out to sea during the night. In the Midwest, Southwest and West, conditions remain normal—searing heat, drought and dangerous levels of ultraviolet radiation.*



RECORDS OF PREVIOUS CLIMATIC CHANGES SUGGEST THAT EVEN A SMALL

If this reads like a newscast from *Saturday Night Live*, it isn't. This report has been extrapolated from carefully considered forecasts for our planet by a wide variety of scientists as we spin toward the 21st century.

Pollutants are saturating our atmosphere. Acid rain, which already has had a devastating impact on parts of eastern North America, central Europe and southern Scandinavia, is one manifestation of this pollution, but its effects tend to be regional. Two similar and interrelated pollutant threats loom even larger, and they may soon affect life on a global scale. Both have the potential of wreaking catastrophic change on the earth's climate—and on life.

The first of these threats is the pollution caused by the release of chlorofluorocarbons into the atmosphere. These man-made chemical compounds—more commonly called CFCs—are used as refrigerants and coolants and in the manufacture of everything from pillows to polystyrene boxes for fast food. Ever since their invention not quite 60 years ago, CFCs have been rising into the stratosphere. When they hit the protective cover known as the ozone layer—10 to 20 miles up—they raise hell because their chlorine component devours the molecules that form the thin ozone shell. As that layer is depleted, stronger and stronger doses of ultraviolet (UV) radiation from the sun are able to penetrate to the earth's surface. Skin diseases and

RISE IN GLOBAL TEMPERATURES COULD HAVE ENORMOUS REPERCUSSIONS

plant destruction are only the beginning of the troubles that excessive UV radiation can cause.

The other major threat is caused by the continuing buildup of carbon dioxide, nitrous oxide and trace gases, including CFCs, in the atmosphere. In the 150 or so years since the industrial revolution, man's activities have enormously increased the atmospheric concentrations of these gases. The rapidly expanding use of fossil fuels and the vast destruction of the earth's forests have combined to create a great effusion of these so-called greenhouse gases. They are given that name because when they rise into the atmosphere, they form a kind of blanket in the sky that lets in solar heat but prevents heat from escaping the earth's atmosphere — much like a giant greenhouse. The resulting rise in air temperatures could create havoc.

This is not the stuff of the far-off future, either. To the alarm of many scientists, a seasonal hole has begun to appear in the ozone layer above the Antarctic. When a significant drop in the ozone level was first recorded in 1978, the scientists who made the observations didn't pay much attention to their own data because no one had foreseen the possibility of such a thing. Unlike the ozone hole, the greenhouse effect was something scientists had anticipated, but it is developing faster than expected. In fact, Dr. James Hansen of the NASA Goddard Institute for Space Studies in New York flatly says that within 10 to 15 years the earth will be warmer than it has been in 100,000 years. Clearly, changes are under way. Whether they will be moderate or catastrophic depends on how man responds.

CFCs were invented in 1930 by the late Thomas Midgley, who left another dubious legacy: tetraethyl lead for gasoline. Midgley came up with CFCs when the Frigidaire division of General Motors asked him to find a safe replacement for the toxic ammonia then used in refrigerators. When Midgley's discovery was placed on the market, it was quickly hailed as a miracle compound, and similar substances were created and adapted for a wide variety of industrial applications. Besides serving as refrigerants, CFCs came to be used as foaming agents, blowing and cleaning agents and as propellants in aerosol sprays. Now they are literally all over the place. The major industry trade group, called the Alliance for Responsible CFC Policy, notes that chlorofluorocarbon refrigerants are used to cool 75% of the food consumed in the U.S., as well as for air conditioning in residential, industrial and automotive applications. They are used as solvents to clean microchips and printed circuit boards and are mixed with ethylene oxide to produce a nonflammable gas that sterilizes hospital and pharmaceutical equipment. The same gas blend is also used as a fumigant and pesticide in granaries, warehouses and ships' cargo holds. CFCs are used extensively in the production of plastic foams that insulate buildings, pipelines, storage tanks, railroad cars and trucks; likewise the foams in pillows, cushions, mattresses and the padded dashboards of cars, in egg cartons and in containers and cups for hot foods and beverages. When CFCs escape from discarded air conditioners and refrigerators, or when a bulldozer in the town dump crunches a discarded foam pillow or old mattress, the substances containing the CFCs are broken down, and the chlorofluorocarbons enter the atmosphere to do their dirty work in the ozone layer.

The most outspoken scientist on ozone depletion is a chemist named Sherwood Rowland. After receiving a

PHOTOGRAPHS BY RYSZARD HOROWITZ

Ph.D. at the University of Chicago. Rowland, now 60, earned an international reputation in radiation chemistry. In 1964 he became chairman of the chemistry department at the University of California at Irvine. When he attended an Atomic Energy Commission meeting on atmospheric research in Fort Lauderdale in 1972, he was casting about for new fields to explore. At the AEC conference Rowland learned that James Lovelock, the unorthodox British scientist best known today as the father of the Gaia hypothesis (that all life on earth should be considered a single living entity), was going to report in the journal *Nature* that he had measured CFC levels in the lower atmosphere. In his paper, Lovelock suggested that CFCs might be used as atmospheric tracers, but he pronounced them "no conceivable hazard." Rowland was intrigued by the report; he had done research on fluorine, which is one of the components of chlorofluorocarbons, as well as in photochemistry (the action of light on chemicals), and he thought it might be interesting to study the eventual fate of CFCs in the atmosphere.

When Rowland began his investigation at UC Irvine in October 1973, the annual production of CFCs in the U.S. was on the order of 850 million pounds. DuPont, which sold them under the trade name Freon, was the major domestic manufacturer. Rowland did his initial research with Mario Molina, a postdoctoral student who had just received his Ph.D. from Berkeley. By December of that year the two scientists had completed their research, and in June 1974 they published a paper in *Nature*. The results of their research were startling, but as Rowland says, "There was no moment when I yelled 'Eureka!' I just came home one night and told my wife, 'The work is going very well, but it looks like the end of the world.'"

Briefly put, Rowland and Molina reported that CFCs were being added to the environment in steadily increasing amounts, that they aren't destroyed in the troposphere (the lower atmosphere), and that they survive for many decades, slowly drifting up into the stratosphere. Once CFCs reach the stratosphere, though, UV radiation decomposes them and releases chlorine atoms. This in turn triggers a catalytic chain reaction in which a single chlorine atom can destroy hundreds of thousands of molecules in the ozone layer before it eventually falls back to earth.

Ozone is constantly created by the action of sunlight on oxygen molecules, but over time chlorine atoms from relatively few decomposed CFCs can destroy more stratospheric ozone than the sun can create. The ozone layer is shifting and amorphous. It is thinnest and reaches its maximum altitude in the high stratosphere over the tropics, which is where most of the ozone is produced. The layer is at its lowest over the poles.

Rowland and Molina pointed out in their 1974 report that almost all the CFCs that had been released since the 1930s were still in the lower atmosphere, and thus the effect on the ozone layer could be expected to intensify in the future. Last May, Rowland told a joint hearing of the Senate Subcommittee on Environmental Pollution and the Senate Subcommittee on Hazardous Wastes and Toxic Substances that certain CFC compounds, notably CFC-11, CFC-12 and CFC-113, "have lifetimes in the lower atmosphere that range from 75 to 120 years. . . . A 120-year average lifetime, without any intervening major changes in the atmosphere, means that . . . even without any further emission of [CFC-12] . . . and releases are occurring daily all over the world sufficient to average about 400 kilotons annual-

DEFORESTATION AND THE USE OF FOSSIL FUELS HAVE CAUSED A HUGE

ly appreciable concentrations will survive in the atmosphere for the next several centuries.

But the publication of the Rowland-Molina report was just the beginning of the battle against CFCs. The Governing Council of the United Nations Environment Programme convened a panel of experts to examine the problem in 1977. The following year Canada, Sweden and the U.S. banned the use of CFCs in aerosol sprays (but only a few other countries have followed suit and CFCs from aerosol sprays still account for about 15% of the global total according to the Environmental Defense Fund). In March 1985, after eight years of continued UN-sponsored meetings, the U.S. and 20 other countries signed what is now known as the Vienna Convention for the Protection of the Ozone Layer. The convention called for international cooperation in research and monitoring. It also provided for the adoption of international protocols to limit the emission of ozone depleting substances should such measures be necessary. Richard Benedick, a career diplomat who was the American deputy assistant secretary of state for environment, health and natural resources, signed the document for the U.S., calling it "a landmark event. It was the first time that the international community acted in concert on an environmental issue before there was substantial damage to the environment and health."

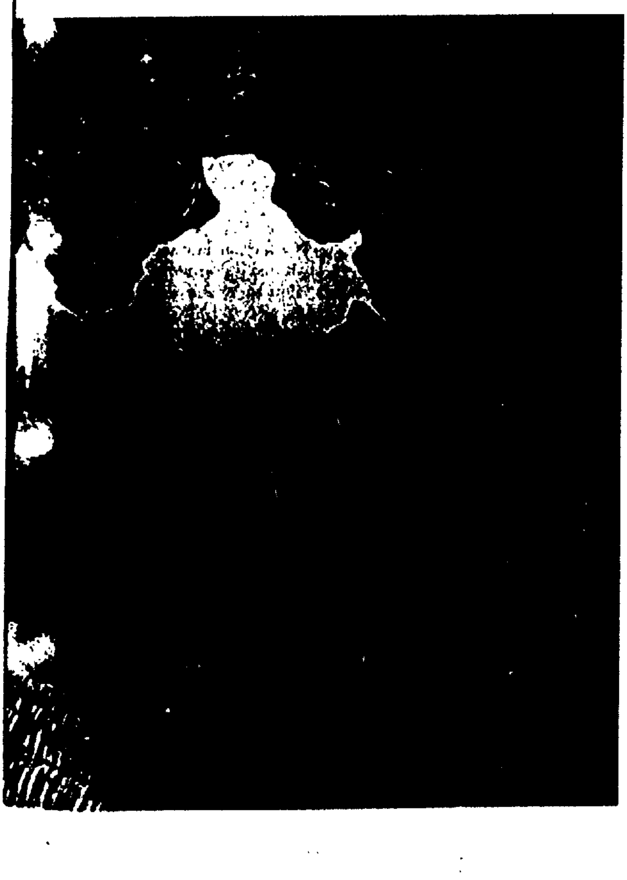
Two months later, in May 1985, *Nature* published alarming new information about CFCs. This paper was written by Dr. Joe Farman, an atmospheric scientist with the British Antarctic Survey, which had been routinely measuring the ozone layer above the Antarctic since 1957. He and others examined the data and saw that in recent years the ozone levels in September and October (the Antarctic spring) had fallen considerably.

The British measurements came from ground based observations, and the ways Farman wondered if NASA satellites had recorded the phenomenon from space. At first it appeared that they had not. However, further checks of NASA computer data revealed that the hole in the ozone layer was apparent as early as October 1978 — the first year in which such satellite comparisons could be made — and had reappeared each year at roughly the same time. The Farman paper suggested that the ozone drop might be tied to CFCs. But other scientists thought the unique weather dynamics above Antarctica were a more important factor. In August 1986, Dr. Susan Solomon, an atmospheric chemist with the National Oceanic and Atmospheric Administration, led a team of scientists to the Antarctic to study the hole. At its maximum it was the size of the U.S. The scientists also noticed that some ozone depletion extended as far north as Tierra del Fuego and Patagonia. This past August four more teams traveled to Antarctica to make further observations. Although scientists are still going over their data, there now seems to be general agreement that the ozone hole is caused primarily by chlorine from CFCs.

Depletion of the ozone layer increases the amount of ultraviolet radiation reaching the earth, and the potential effects on human health are considerable. First, there's skin cancer. It is the most common form of cancer in this country, with an estimated 500,000 cases discovered each year. A study published by the Environmental Defense Fund projects that by 2025 there will be an additional 1.4 million incidences of skin cancer over the present rate if nothing is done to control ozone depletion.

Cataracts are another threat posed by elevated UV levels. So is alteration of the immune system. Research on

INCREASE OF CARBON DIOXIDE, PROMOTING THE GREENHOUSE EFFECT

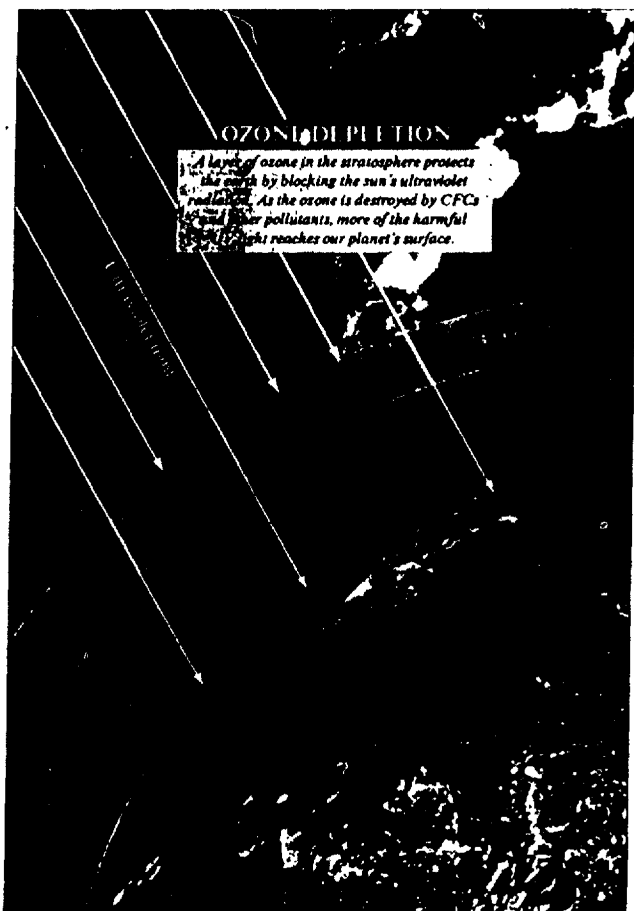


the effects of UV radiation on the immune system has been done using mice as subjects. According to congressional testimony by Dr. Margaret L. Kripke, chairman of the department of immunology at the University of Texas.

There is considerable evidence that the UV rays damage a type of immune cell found in the skin, the Langerhans cell, and that this damage leads to activation of suppressor lymphocytes instead of the appropriate immune response. Thus although the initial damage is localized to the area of skin exposed to the UV radiation, the resulting immunological suppression is systemic, because the suppressor cells circulate throughout the body."

Not only mankind is at risk. Experiments with marine organisms have shown that UV radiation can damage animals in the marine food chain. The potential for damage to vegetation is also high. Dr. Alan Teramura, a professor of physiological ecology at the University of Maryland, reports that although some plants may adapt to UV radiation, many are adversely affected by increased levels. In tests, higher levels of UV radiation caused plant stunting, reduction in leaf area and reduced physiological vigor—the latter rendering them more vulnerable to pests and disease. In a six-year study of soybeans, UV radiation was increased to simulate a 25% reduction in the ozone layer, the result was a 20 to 25% loss in yields.

"Unlike drought or other geographically restricted stresses, increases in UV would affect all areas of the world simultaneously," Teramura says. "Even small reductions in crop yield on a global basis could lead to considerable economic consequences." Almost all knowledge of the effects of UV on plants comes from studies of cultivated crops, but these account for less than 10% of the world's vegetation. We have little or no information on the effects on the other 90%—the forests, grasslands and shrublands. In fact, there is much we don't now know about the extent of the damage that may be done by CFCs rising into the sky, because nothing like it has ever happened before. But when it comes to massive changes in climate, there are some precedents that may give us signs of what to expect.



Over the last 2,000 years, the earth has undergone two major changes in climate. The first was a warm period known to scientists as the medieval warm epoch; it occurred between the years 800 and 1250, when average global temperatures were about the same as they are now. Certain areas, however, were distinctly warmer. During that time barley and oats were grown in Iceland and vineyards flourished in England, where sea levels were gradually rising. In Belgium the rising sea made Bruges, now some 15 miles inland, a seaport.

Around 985, the Vikings began to colonize Greenland, which had been discovered by Eric the Red. But by the end of the 13th century Arctic sea ice had spread through Greenland's waters and had become such a navigational hazard that the colonies died out.

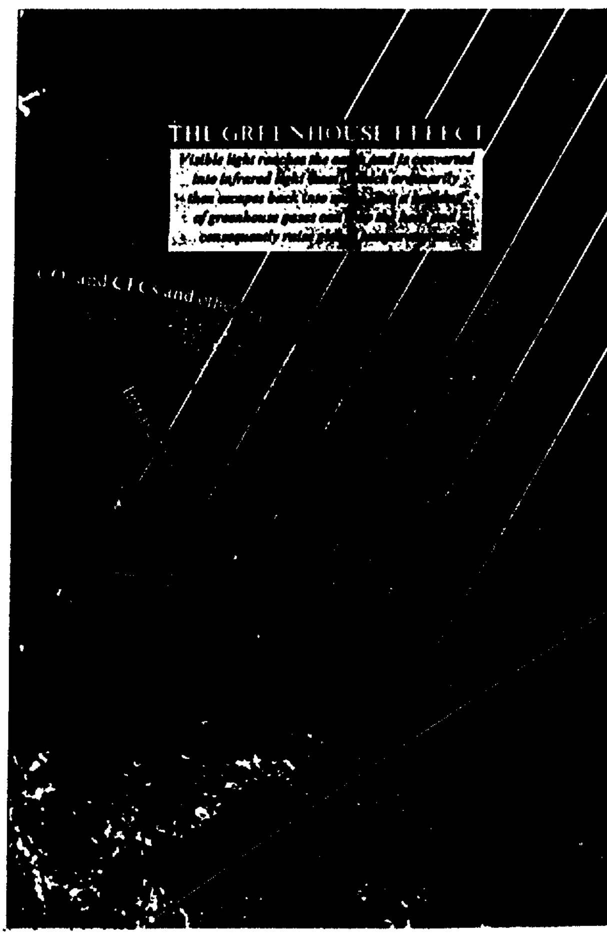
The medieval warm epoch was soon followed by the Little Ice Age, which lasted from about 1550 to 1850, during which the global climate was generally about 1 C (2°F) cooler than now In India, the monsoons often failed to arrive, prompting the abandonment in 1588 of the great city of Fatehpur Sikri because of lack of water The Thames froze over several times in the late 1500s Year-round snow, now absent, covered the high mountains of Ethiopia The vineyards of northern France died off

Some scientists who have studied the earth's climatic cycles believe that around 1700, when the Little Ice Age began its gradual decline, the earth swung into a period of 1,000 years of natural warming This forecast, however, does not take into account the effect of *unnatural* agents, such as the increasing concentrations of carbon dioxide, nitrous oxide and other greenhouse gases in the atmosphere

What's happening is this Light from the sun passes through these transparent gases to the earth, where the short-wave radiation (light) becomes long-wave radiation (heat) The heat rises from the earth and ordinarily would escape into space However, greenhouse gases absorb the long-wave radiation. Thus, the more these gases accumulate in the atmosphere, the more heat they absorb, and the warmer the earth becomes. In time, the planet will come to be like a greenhouse—or a car parked with its windows up on a sunny day

The theory that increasing levels of carbon dioxide could cause this greenhouse effect was first advanced in 1896 by a Swedish physicist and chemist named Svante Arrhenius However, the idea took on startling new significance in 1958 when Charles D Keeling, a chemist and professor of oceanography at the Scripps Institution of Oceanography began measuring atmospheric carbon dioxide on Mauna Loa in Hawaii Since Keeling's measurements began, the concentration of the gas has increased every year It jumped from 315 parts per million (ppm) in 1958 to 349 in 1987 a 25% increase from the levels that are thought to have been present before the industrial age The increase is attributable to a combination of the burning of fossil fuels and the destruction of forests, which serve as reservoirs of carbon A forest stores about 100 tons of carbon per acre and in the last 40 years it is estimated that as much as half the world's forests have been destroyed Given current emission levels the atmospheric concentration of carbon dioxide is expected to reach about 420 ppm by the year 2030

Two other greenhouse gases CFCs and nitrous oxide are double whammies They are involved in the depletion of the ozone layer (in the case of nitrous oxide this is true only when the gas mixes in the atmosphere with CFCs or carbon dioxide) and they absorb heat Measured in the range of parts per trillion CFC concentrations



might seem insignificant, but they are extraordinarily effective heat absorbers. One molecule of CFC-11 or CFC-12 can trap as much heat as 10 000 molecules of carbon dioxide. And CFC levels are increasing at the rate of 5 to 7% per year.

Ground-level ozone also qualifies as a greenhouse gas. It is formed by the action of sunlight on nitrogen oxide and hydrocarbon pollutants emitted primarily by cars and trucks. We call it smog. Ozone has a split personality. Stratospheric ozone protects life by shielding the earth from harmful UV radiation; ground-level ozone is toxic. In the U.S. alone, according to a study made by the Environmental Defense Fund, ozone pollution is responsible for annual losses of as much as $2 billion in wheat, corn, soybeans and cotton. Ozone produced on earth cannot be used to replenish the ozone layer in the stratosphere because it has a limited life span before combining into other chemical substances. Therefore it doesn't last long enough to accumulate in amounts significant enough to replace what's being lost in the stratosphere.

In the last 100 years, the global mean temperature has gone up by about 0.5°C. Even if all emissions of greenhouse gases were cut off today, past emissions already make another 0.5°C increase likely by 2050. According to computer model estimates done by Dr. Veerabhadran Ramanathan, an atmospheric scientist at the University of Chicago, the global average surface temperature could increase by a total of as much as 4.5°C in the next 40 years based on current levels of greenhouse gas emissions. That would make the earth almost as hot as it was during the Cretaceous period, the age of the dinosaurs, 100 million years ago. Mind you, that is the global average. The greatest increase in temperatures will occur from the mid-latitudes to the poles, where wintertime averages could be 10°C higher than now.

Hansen, of NASA's Goddard Center, uses a climate model that predicts a temperature increase averaging 1° to 2°C in the U.S. by the middle of the 21st century. He also has created a computer model that predicts temperature increases for a number of U.S. cities. By around 2050—give or take a couple of decades because the role of the oceans is not yet predictable and could delay the warming effect—Washington, D.C., which according to Hansen's model has about 36 days a year when the temperature exceeds 90°F, will have 87 such days. Omaha, with 37 days over 90° now, will have 86. New York, with 15 now, will have 48. Chicago, with 16 now, will have 56; Denver, with 33, will have 86; Los Angeles, with 5, will have 27; Memphis, with 65, will have 145; Dallas, which has 100, will have 162. Hansen's model similarly shows an increase in 100°F days: Washington goes from 1 a year to 12, Omaha from 3 to 21; New York from 0 to 4, Chicago from 0 to 6; Denver from 0 to 16, Los Angeles from 1 to 4, Memphis from 4 to 42; and Dallas from 19 to 78.

"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," Hansen says. "We believe that the temperature changes themselves will substantially modify the environment and have a major impact on the quality of life in some regions. ... However, the greenhouse issue is not likely to receive the full attention it deserves until the global temperature rises above the level of the present natural climate variability. If our model is approximately correct, that time may be soon—within the next decade."

Dr. Wallace Broecker, a geochemist at the Lamont-Doherty Geological Observatory of Columbia University, thinks the situation may be even worse than indicated by models, with their supposition of a gradual warming over a considerable period of time. "The earth's climate doesn't respond in a smooth and gradual way," he says. "Rather, it responds in sharp jumps. These jumps appear to involve large-scale reorganizations of earth systems. If this reading of the natural record is correct, then we must consider the possibility that the major responses of the earth system to our greenhouse provocation will also occur in jumps whose timing and magnitude are uneven and unpredictable. Coping with this type of change is clearly a far more serious matter than coping with a gradual, steady warming."

These models are far from perfect—none of them was able to predict the ozone hole over the Antarctic, for example—but, for now, they're our best source of information about changes we can expect to see by the year 2050. The view is not pretty.

Climate modeling done by Dr. Syukuro Manabe, an atmospheric scientist at the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory in Princeton, N.J., led him to testify before a congressional committee in 1985 that "winters in Siberia and Canada will be less severe. Because of the penetration of warm, moisture-rich air into the high latitudes, a doubling of atmospheric carbon dioxide or the equivalent might increase the rate of river runoff in northern Canada and Siberia by 20 to 40 percent. Our climate model also indicates that in response to the increased greenhouse gases summer drought will become more frequent over the middle continental regions of North America and the Eurasian continent. For example, the model-produced summer drought is characterized by dry soil, reduced cloud cover and higher surface temperature, which resemble the situation during the dust bowl of the 1930s."

A study by the National Academy of Sciences suggests that water volume in northern California rivers and in the Colorado River will decline by as much as 60%. This would leave much of the West without water. Southern California would run dry and be subjected to an increased incidence of fire as would forests throughout much of the West and upper Midwest.

Within the past 100 years tide gauges on the Atlantic Coast of the U.S. have documented a 30-centimeter, or one-foot, rise in sea level. Globally, the average is about five inches. Models predict that the level will have risen by another foot in low-lying coastal regions of the U.S. in 2030 and by as much as three feet in 2100. According to Dr. Steven P. Leatherman, director of the Laboratory for Coastal

UV RADIATION CAUSES SKIN CANCER AND MAY SUPPRESS THE IMMUNE SYSTEM

Research at the University of Maryland, at least part of the present sea-level rise on the East Coast is caused by the natural compacting and subsidence of coastal sediment. But at least 4.5 inches of the rise has been caused by the expansion of warmer ocean surface waters and the melting of mountain glaciers, triggered in part by the 0.5°C increase in global temperature registered during the last century.

Sea-level rise will promote increased coastal erosion. Leatherman says "Already approximately 80 percent of our sandy coastlines is eroding. Artificial nourishment is being used to restore beaches but the costs are high." According to one study that will soon be published, the cost of maintaining East and Gulf Coast beaches will run anywhere from $10 to $100 billion. A series of aerial photographs taken since 1938, for instance, shows that the Blackwater National Wildlife Refuge on the eastern shore of the Chesapeake Bay, one of the most important East Coast waterfowl sanctuaries, is in a state of disintegration because of rising sea level. Human activity can hasten such destruction.

Some of the other threats posed by a one- to three-foot rise in sea level include increased salinity of drinking water, saline intrusion into river deltas and estuaries, which would imperil fisheries, the inundation of wetlands, cypress swamps and adjacent lowlands, increased flooding in populated areas, which would necessitate the building of costly flood protection systems such as sea walls, the disappearance of beaches all over the world.

Then there are these further dire possibilities:

• Studies by meteorologist Kerry Emanuel at MIT indicate that more severe hurricanes are likely because of warmer oceans. Such storms could increase in ferocity by as much as 60% over current maximums.

• Radical change in the Antarctic ice sheet could have severe consequences. Antarctica has 91% of the world's ice (only 1% is locked up in mountain glaciers). If the Antarctic ice sheets were to melt completely, the global sea level would rise 15 to 20 feet. No one expects that to happen. At currently projected rates, the greenhouse effect and global warming are not expected to have a major impact on the Antarctic ice sheet for several centuries. But no one predicted holes in the ozone layer, and as Dr. Stanley S. Jacobs, a senior staff associate at Lamont-Doherty, said in a recent article in *Oceanus* magazine, "Antarctica may be a wild card in the deck, but who can say the deck is not stacked, with Nature setting up the sting?"

Couple all the greenhouse effects with increased ultraviolet radiation and we have written the prescription for disaster: ecological, economical and political.

It is ludicrous to assume that we could rapidly adapt to such changes. "Infrastructures of society, such as water supplies, transportation networks and land use patterns have evolved over centuries in response to prevailing climate," says Dr. Gordon J. MacDonald, a former professor of geophysics at Dartmouth who's now vice-president and chief scientist of the Mitre Corporation, a nonprofit research organization. "Significant changes in climate over decades will exert profound disruptive forces on the balance of infrastructures."

MacDonald is talking about infrastructures that are already in place. But corporations and governments throughout the world are now making big decisions about long-term projects that involve coastal development, massive land use, irrigation, hydroelectric power, oil exploration, natural

RISING SEA LEVELS COULD ADVERSELY AFFECT PORTS LIKE LONDON

gas, etc. Nearly all of these decisions are being based on the notion that the climate of the recent past will continue into the future. This is no longer a safe assumption. In October 1985 the World Meteorological Organization, the International Council of Scientific Unions and the United Nations Environment Programme convened a conference in Villach, Austria, at which more than 80 scientists from 16 countries assessed the climatic changes that could be brought about by the accumulation of greenhouse gases. The scientists concluded that using the climate of the recent past to plan for the future "is no longer a good assumption since the increasing concentrations of greenhouse gases are expected to cause a significant warming of the global climate in the next century. It is a matter of urgency to refine estimates of the future climate conditions to improve these decisions."

Dr. Michael Oppenheimer, a former Harvard astrophysicist who is now senior atmospheric scientist with the Environmental Defense Fund, puts it this way: "We're flying blind into a highly uncertain future. These changes are going to affect every human being and every ecosystem on the face of the earth, and we only have a glimmer of what these changes will be. The atmosphere is supposed to do two things for us: maintain a constant chemical climate of oxygen, nitrogen and water vapor, and help maintain the radiation balance—for example, by keeping out excess UV. The unthinkable is that we're distorting this atmospheric balance. We're shifting the chemical balance so that we have more poisons in the atmosphere—ozone and acid rain on ground level—while we're also changing the thermal climate of the earth through the greenhouse effect and get this simultaneously causing destruction of our primary filter of ultraviolet light. It's incredible. Talk about the national-debt crisis—we're piling up debts in the atmosphere, and the piper will want to be paid."

The fate of the earth rests on political decisions, which doesn't necessarily make it hopeless. Until recently the Reagan Administration has done little to deal with the crisis of atmospheric pollution. When the issue has been addressed, it has been largely at the prodding of individual legislators in the Senate by Republicans John Chafee of Rhode Island, Robert Stafford of Vermont and Dave Durenberger of Minnesota, and Democrats Max Baucus of Montana and George Mitchell of Maine, all members of the Environment and Public Works Committee.

Albert Gore, the Tennessee Democrat who's now a senator, led hearings on the greenhouse effect while he was in the House in 1981, and he's the first current presidential candidate to raise the issue. Indeed Gore's willingness to discuss this politically unpopular subject prompted columnist George Will to chide him for "a consuming interest in issues that are, in the eyes of the electorate, not even peripheral." But as Chafee says, "This is not a matter of Chicken Little telling us the sky is falling. The scientific evidence is telling us we have a problem, a serious problem."

Fortunately, it's still possible to ameliorate the damage. Here's what we must do:

• *Reduce production of CFCs by 95% worldwide within the next six to eight years.* Chafee and Baucus have introduced bills calling for such a reduction. Last winter Chafee told CFC manufacturers: "If the six- to eight-year phase-out in our bills is unrealistic, tell us how much time you need and show us how you will use that time. We are

SOME PREDICTED CHANGES WARMING IN SIBERIA AND DROUGHT IN CALIFORNIA

open to suggestions but the burden is on you to justify a longer time frame Undoubtedly there will be testimony that we cannot ratchet down on production of CFCs too swiftly It is well to recall that the ban on aerosols in the U S caused production of CFCs for aerosols to drop to less than 25 million pounds six years later And our country survived I am not convinced that American or any other producers have a constitutional right to continue to produce products that cause permanent harm to our world, to our citizens

In September the U S and 23 other countries signed a treaty calling for a 50% cut in CFC production by mid-1999 but the new findings from the Antarctic demonstrate that the cut is neither big enough nor fast enough "We've got to beat the clock says Rafe Pomerance a policy analyst who has been following the ozone problem for the World Resources Institute in Washington D C , for the past two years "If the data from the Antarctic continues to build over the next few months, we may have to reconvene and strengthen the treaty

• *Reduce dependence on fossil fuels* We should focus on incremental steps that limit our dependence on coal and oil " Oppenheimer says "Let's focus on the double No 1 conservation The U S still uses twice as much energy per capita as the European nations We're wasting money we're wasting energy and we're producing too much carbon dioxide because of our overdependence on fossil fuels

Reliance on these fuels can also be reduced through greater use of nonpolluting alternative sources of energy Solar power is a prime example but the U S seems to have given up leadership in photovoltaic research and the Japanese are now forging ahead Photovoltaic technology promises to deliver energy at a reasonable price without producing carbon dioxide

• *Halt deforestation* "You have to do two things says Dr George M Woodwell former president of the Ecological Society of America and now director of the Woods Hole (Mass) Research Center "First, you have to stop deforestation around the world, not just in the tropics and you have to do it on the basis of an international protocol Second you have to have an equally intensive and imaginative protocol that calls for reforestation so as to store one billion tons of carbon annually A million square kilometers is 600 miles by 600 miles and we will probably have to reforest on the order of four million square kilometers per year over good land to do the job "

• *Establish a national institute devoted to basic environmental research* Says Oppenheimer "We need a national commitment comparable to the Manhattan Project not only so we can understand what the consequences of global change are for man but so that we can be in the forefront of the development of alternative energy sources that will help limit this problem I envision a multibillion dollar scientific effort It's as important as national defense It is the national defense If we do nothing waiting for the atmosphere to change and for unpleasant consequences to occur it will be too late for us to avoid disruptive and devastating changes "

• *Discontinue basic environmental research by or funded by EPA and the Department of Energy* These agencies are unreliable because they are heavily influenced by political pressures Last January Broecker bluntly told the Senate Subcommittee on Environmental Protection "I believe that most scientists would agree with me that the handling of research on greenhouse gases by DOE [the Department of Energy] and on acid rain by EPA has been a disaster

Will the world act in time? As Rowland who won eight varsity letters in basketball and baseball at Ohio Wesleyan and the University of Chicago, puts it "The key thing about baseball is there is always next year another season The question for the earth now is will there be a next year?" ■

A24 Saturday, June 11, 1988

The Washington Post

AN INDEPENDENT NEWSPAPER

Living in a Greenhouse

LAST YEAR was, worldwide, the warmest on record. The four warmest years in modern history all fall in the 1980s. There's a good deal of uncertainty about the rate at which this planet is getting hotter, but there's no doubt about the direction of the trend, or the reason for it.

The ingenious inhabitants of this world have brought themselves to a level of industrial development that is changing the climate. The chief cause is the gigantic volume of carbon dioxide that they generate by burning all the familiar fuels, but there are other gases that also make important contributions to the temperature. They are building up into a chemical blanket through which the very high frequency radiation from the sun passes easily, but which traps the heat that the Earth would radiate back at lower frequencies into space. That's the greenhouse effect—the chemical blanket has the same effect as a sheet of glass—and the speed with which it changes climates will depend on the world's ability to reduce the emissions that are feeding it.

Temperatures worldwide have swung up and down sharply over the centuries for entirely natural reasons. In recent history the world got colder in the 17th century, on the whole an unpleasant time to live, and hit a low point early in the 18th. It grew warmer for a century, then dipped again in the early 19th century and since then, in an irregular and unpredictable pattern, has been getting warmer. In recent years man-made emissions of insulating gases have apparently begun to overwhelm whatever natural process might be at work. The present changes in the world's average temperatures are measured in tenths of a degree Centigrade per decade, but a few tenths of a degree is enough to affect the climate perceptibly. The warming since the last Ice Age may have been no more than 5 degrees, and in the past two centuries, geologists have seen glaciers advance and retreat in response to variations of a fraction of a degree.

A prolonged warming trend would mean a rising sea level, changes in patterns of precipitation and perhaps even changes in vegetation. With the return of summer, perhaps it's a good moment to ask how far this process of unintended change will be allowed to run.

Congress has asked the Environmental Protection Agency for two reports, one describing the greenhouse effects now unfolding and the other on the possibilities of restraining and stabilizing the accumulation of greenhouse gases. The reports are to be published at the end of the year, just in time for the arrival of the next administration.

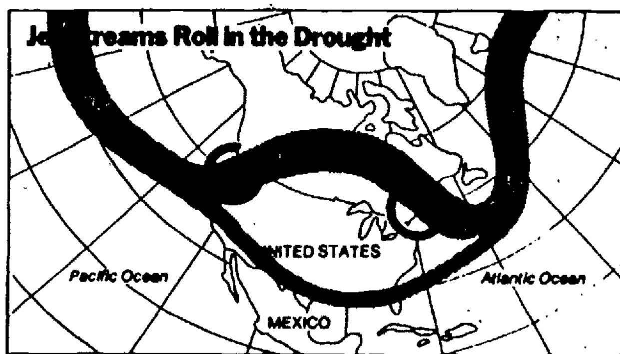
Climate Experts Ask If Drought Presages 'Greenhouse World'

By WALTER SULLIVAN

Weather specialists studying the drought in the Middle West this year have determined why it occurred. But they are wondering whether it is a harbinger of things to come, perhaps evidence of basic changes in climate brought about by the "greenhouse effect."

For months a great wall of high pressure air over the central United States has prevented storms bearing rain and snow from penetrating that region, according to specialists of the National Weather Service. The high pressure was locked in place by a jet stream far north of its normal position.

As a result, the agency said yesterday, precipitation has been abnormally high in the Northeast and the Northwest even as the Middle West has suffered.



The New York Times

The current drought resulted when the jet stream, which directs storm activity, split to flow around a dominant high pressure zone in the middle of the country. The stream brought storms to areas such as those indicated by dark circles but not to the Middle West.

A Change in the Weather?

Concern was expressed yesterday that the resulting drought might offer a glimpse into what Dr. Alan D. Hecht, the director of the National Climate Program Office in Rockville, Md., called "the greenhouse world" of the future.

Is the drought, he asked, "the kind of thing we will see more of?"

A number of weather specialists have been searching for signs that world climate is changing as a result of warming caused by carbon dioxide from the burning of fuel. This is the much-discussed greenhouse effect.

With the information now available, Dr. Hecht said, an obvious relationship is still uncertain.

Dr. Hecht, whose office is part of the National Oceanic and Atmospheric Administration, said he hoped Dr. Charles W. Stockton at the University of Arizona could determine, from the widths of annual tree rings in much of the West, whether droughts in the last three centuries had been as prolonged and widespread as this one.

Not since the dust storm period of the 1930's, Dr. Hecht said, has a drought been so extensive. He would like to know how exceptional this one is.

Rings and Rainfall

Annual rings in trees growing in the region over the last 300 years have been analyzed at Dr. Stockton's Laboratory of Tree-Ring Research at the University of Arizona. Researchers are trying to find out whether occurrences of narrow rings, indicating drought, conform to a 22-year cycle of solar activity. The results have been inconclusive.

David Miskus of the Analysis and Information branch of the National Weather Service said that from December to February a high pressure region off the West Coast had kept storms away, leading to low precipitation there.

The high pressure wall then moved east to its present position over the central states.

In winter and spring, according to Dr. Donald Gilman, long-range forecaster of the Weather Service, the jet stream normally heads east after crossing California, carrying storms over the Middle West.

This year, however, the jet stream has split, Dr. Gilman said. The main branch has swung north across Oregon. Near Hudson Bay it has curved southeast across New Hampshire and has joined the lesser branch over the Atlantic Ocean after the latter has crossed northern Mexico and Florida.

The drought now affects most of the Mississippi-Missouri drainage systems, reaching from Canada to the Gulf of Mexico. The rivers are extremely low. The Tennessee Valley has been short of rain for several years, according to Dr. Gilman, and the shortage has lowered reservoirs enough to threaten power production.

Africa, Asia to Suffer Most From 'Greenhouse Effect,' Study Says

THE WASHINGTON POST

A10 TUESDAY, JUNE 7, 1988

By Michael Weisskopf
Washington Post Staff Writer

Global temperatures would rise one-half degree and sea levels increase more than two inches every decade if "greenhouse gases" that trap heat are released at current levels, according to a scientific report released by the United Nations yesterday.

The projected increases dwarf those of the last century, and their impact is expected to be greatest in three general areas:

- Semi-arid regions of Africa, where hotter days would aggravate famine and drought.
- Humid, tropical parts of Asia, where higher sea levels would increase risk of flooding.
- High latitudes of Alaska, Canada and Scandinavia, where more extensive ice thaws would complicate everything from marine transportation to construction practices.

A more moderate outcome is expected in mid-latitude regions, including the United States and central Europe, where the report predicted thinning of forests and local disruption in agricultural productivity.

"We're leaving a period in which the Earth and the human enterprise have passed through substantial climatic stability over centuries into a period of very rapid change," said George Woodwell, director of the Woods Hole Research Center and contributor to the report published by the U.N. Environmental Programme and World Meteorological Organization.

The report grew out of two international workshops attended last year by top scientists and government officials asked to refine projections of the "greenhouse effect" and to recommend policy steps to curb it.

Scientists have long warned that carbon dioxide released from coal and other fossil fuels burned for energy accumulate in the atmosphere with such man-made pollutants as nitrous oxides, methane and chlorofluorocarbons (CFCs), trapping incoming sunlight much like a greenhouse and warming the temperature.

Although scientific bodies have predicted that doubling emissions of greenhouse gases would increase the world's temperature 6 degrees and raise sea levels, yesterday's report is the first to estimate how fast and where changes would occur.

The study projects different climatic outcomes for different levels of pollution. The half-degree increase per decade is based on current emission trends and implementation of an international agreement to halve CFCs over the next decade. Temperatures rose at one-sixth of that level in the last century.

With a significant increase in emissions of greenhouse gases, such as a five-fold increase in coal use by 2025, temperatures would increase about 1.5 degrees per decade, according to the report.

Stringent global pollution controls, such as halving carbon-dioxide emissions by 2075, would result in a slight temperature increase.

"Without exception, you see that all of those are rising trends," said William C. Clark, a Harvard University ecologist and study participant. He said rapid growth of greenhouse gases would result by 2040 in temperatures warmer than "anything we've seen on Earth since human societies were developed . . . ."

Warming trends vary regionally, with upper latitudes of the Northern Hemisphere facing the most extreme temperature increases in the winter, as much as 2½ times greater and faster than the global average.

Temperature increases in the mid-latitudes, including the United States, would be close to average in summer while somewhat higher than average in winter.

While sea levels would rise 2.2 inches per decade at current levels of pollution, the increase would be 9.4 inches every 10 years with rapid growth of the gases. Strong controls would result in slight decreases.

Any rise in sea levels would aggravate the erosion of beaches, reduce available land for such activities as salt making, decrease wetlands, and increase flooding and damage to port facilities, the report said. Woodwell said the impact would be most severe in the deltas of Louisiana and along the Florida coastline.

Michael Oppenheimer, an atmospheric physicist at the Environmental Defense Fund who participated in the study, said a solution must be implemented as soon as possible including cutting by nearly one-third the amount of fossil fuels burned yearly.

LOOKING AHEAD

A WARMING WORLD:

Rising global temperatures could disrupt wheat farmers, electric utilities, and military strategy. Which companies win or lose depends on how well they plan ahead. ■ *by Anthony Ramirez*

A PHYSICAL CHILL settled on the 14th century at its very start, initiating the miseries to come. The Baltic Sea froze over twice, in 1303 and 1306–7, years followed of unseasonable cold, storms, and rains, and a rise in the level of the Caspian Sea. Contemporaries could not know it was the onset of what has since been recognized as the Little Ice Age lasting until about 1700. Nor were they yet aware that, owing to the climatic change, communication with Greenland was gradually being lost, that the Norse settlements there were being extinguished, that cultivation of grain was disappearing from Iceland and being severely reduced in Scandinavia.

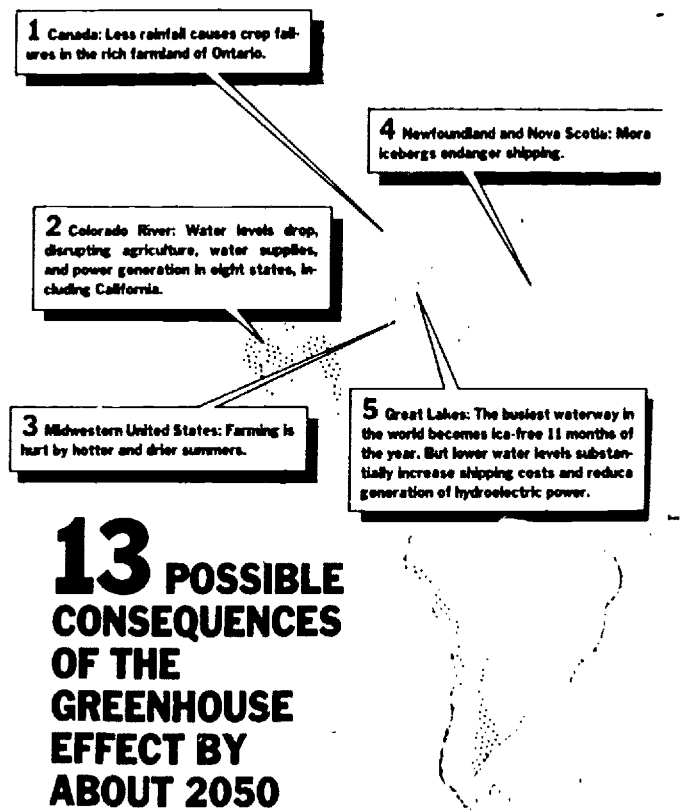
– Barbara Tuchman, A Distant Mirror

Like the 14th century, the 21st century is in for nasty weather—but of the opposite kind. Although the earth has undergone periods of warming and cooling in the past, scientists are now generally agreed that it is about to heat up more—and faster—than ever. By the likeliest scenario the resulting climatic changes will bedevil farming, shipping, international trade, energy policy, and military strategy. Coping with dramatic global warming will not be easy, but ignoring it would be foolish. The best bets: conserving energy and using alternative energy sources, including nuclear power.

The threat is clear. Carbon dioxide from the burning of fossil fuels like oil, coal, and gasoline is rapidly accumulating in the atmosphere. So are gases like chlorofluorocarbons (CFCs), which are far less abundant but equally devastating. CO_2, CFCs, and the other gases come almost entirely from a variety of man-made sources like vehicle exhausts and industrial solvents. Only a modest amount derives from natural sources like microbes in the soil. In the earth's atmosphere the gases act like the glass in a greenhouse, which lets in sunlight but traps heat. By absorbing rather than reflecting the infrared radiation that produces heat, they are bringing about the relentless warming of the planet known as the greenhouse effect (see box, page 104).

"My feeling is that there's no way to stop it," says Walter Roberts, president emeritus of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, and an organizer of a year-long United States–Soviet Union conference on global warming that started meeting in May. "It may be a little bit smaller or it may be a little bit larger. But the greenhouse effect is going to come." He thinks global dependence on fossil fuels is so vast that it makes

REPORTER ASSOCIATE *Alicia Hills Moore*



13 POSSIBLE CONSEQUENCES OF THE GREENHOUSE EFFECT BY ABOUT 2050

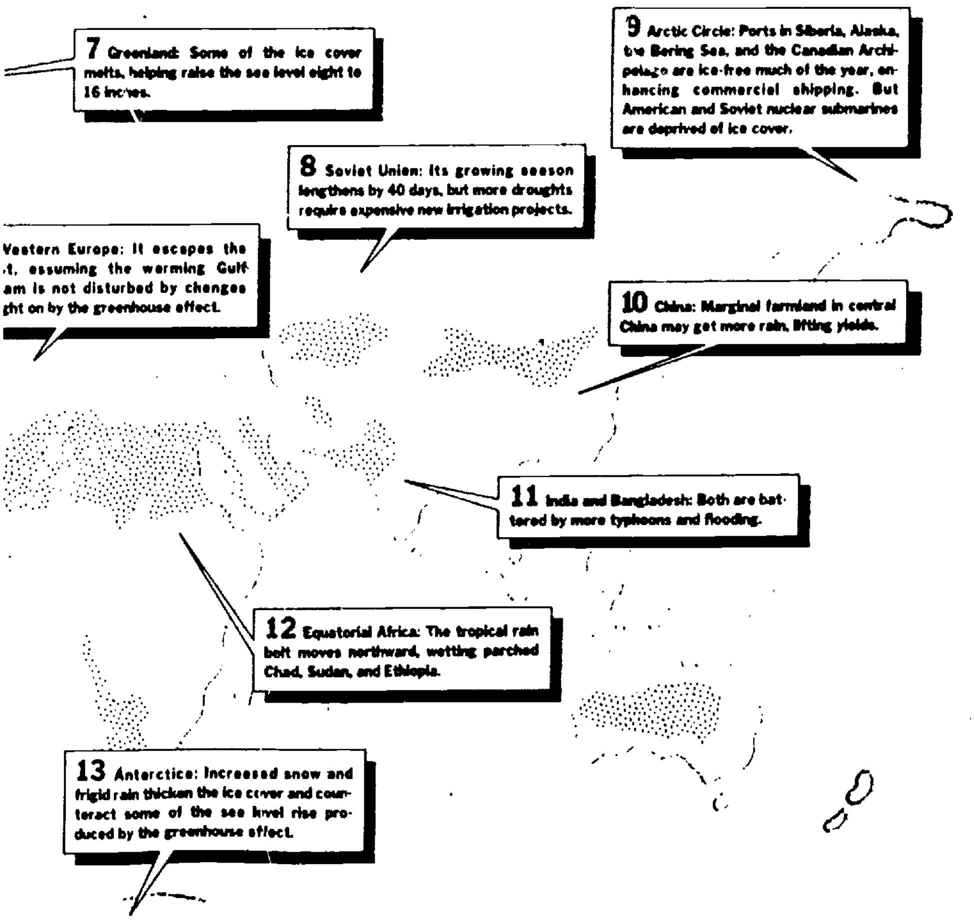
WHAT IT WILL MEAN

serious international cooperation to reduce CO_2 emissions unlikely

Because no one understands all the variables that alter the earth's temperature, it's not absolutely certain that the greenhouse effect will arrive as predicted or that all its dire projected consequences will actually occur (see box, page 106). Some mitigating factors exist today, and others may emerge as the effect grows. For example, while clouds high in the atmosphere tend to trap heat, low-lying clouds tend to reflect sunlight. Clouds with a high moisture content have an even greater cooling effect.

Even so, the signs are ominous. Measured by the global mean temperature, last year was the warmest year on record; the 1980s are the warmest decade in a century. A rise in the earth's temperature of at least 2° or 3° Fahrenheit seems inevitable by the mid-21st century, when the concentration of CO_2 in the atmosphere is likely to be some 60% greater than today and double the level that prevailed before the Industrial Revolution. A temperature increase of more than 8° F is possible.

Just a 2° warming could have dramatic effects. Since that 2° is only an average figure, much larger temperature increases could occur in certain places and seasons. For in-



LOOKING AHEAD

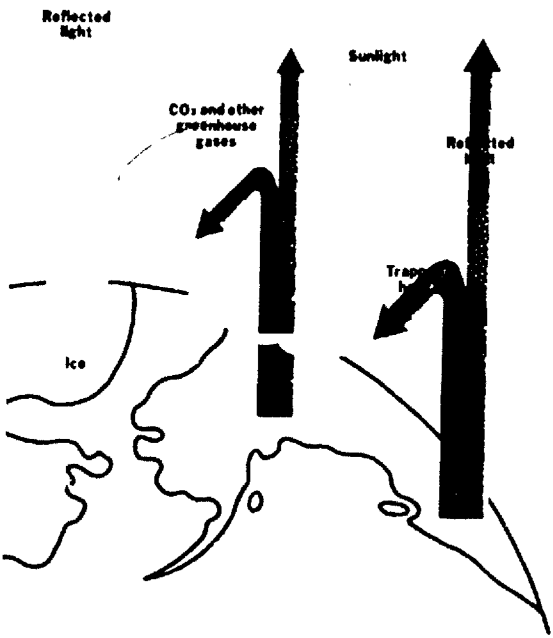
stance one NCAR computer simulation projects a hot spot near the Bering Sea that could be nearly 30° warmer in winter than today. It took a worldwide cooling of only about 2°, perhaps due to a drop in solar radiation, to cause the Little Ice Age that wrought havoc in the 14th century. That was only a minor wobble compared with the long-term oscillations that occur over many millenniums. A seemingly small temperature shift means the difference between balmy spells and true ice ages. Civilization has developed in a narrow band of global climate, never more than 3° warmer or cooler, on average, than today's. A warming of 7° over the next 60 years or so would equal the entire rise in global temperature since the glaciers began their long retreat 18,000 years ago.

THE GREENHOUSE EFFECT will disturb the climate of the planet, changing such critical variables as rainfall, wind, cloud cover, ocean currents, and the extent of the polar icecaps. Although country-by-country consequences are far from clear, scientists are confident of the overall trends. Interiors of continents will tend to get drier and coasts wetter. Cold seasons will shorten, warm seasons lengthen. Increased evaporation will lead to drier soils over wide areas.

The ripple effects through the world economy will be enormous as shifts develop in soil conditions, crop yields, salinity of water supplies, and the availability of river water for generating hydroelectric power. Engineers will be hard put to it to anticipate future stresses on structures they build. "It may become difficult to find a site for a dam or an airport or a public transportation system or anything designed to last 30 to 40 years," says Jesse Ausubel, director of programs at the National Academy of Engineers. "What do you do when the past is no longer a guide to the future?"

Government officials and corporate executives are slowly becoming aware of the hazards of the greenhouse effect, but few are thinking of long-term strategies. Global warming was a minor item on the agenda of the Reagan-Gorbachev summit last December; the U.S. and the Soviet Union agreed to produce "a detailed study of the climate of the future."

Weyerhaeuser, the giant forest-products company in Tacoma, Washington, worries about its nearly two million acres in Oklahoma and Arkansas, where some climate scientists project a warming, drying trend



HOW THE GREENHOUSE EFFECT WORKS

The earth grows warmer or colder mainly because of the effects of sunlight in the atmosphere. Clouds, snow, and ice reflect some sunlight back into space. But the earth absorbs much of it, converting it into infrared energy—heat. As heat rises from the earth's surface, it strikes molecules of carbon dioxide and other gases, setting them vibrating. The gas molecules reflect some of the heat back to earth, intensifying the warming effect. (For simplicity, the illustration shows the gases as a band in the atmosphere; in fact they occur throughout it.)

The more CO_2, the greater the heating. The earth's atmosphere contains substantially more CO_2 than it did before the Industrial Revolution. By analyzing cores from the ice sheets that cover Greenland and Antarctica, which enclose trapped bubbles of centuries-old atmospheric gases, scientists have concluded that in 1750 the atmosphere contained about 280 parts per million of CO_2. Today the figure is 344 ppm, nearly 25% higher.

If that trend accelerates, as most scientists now believe it will, at some point between 2030 and 2070 concentrations of CO_2 will rise to between 1.3 and 1.9 times the preindustrial level, or 367 to 531 ppm. In general, the stronger the world's economies, the more CO_2 gets spewed into the air. Scientists consider the near doubling of CO_2 more likely than the modest increase.

While CO_2 produces half the greenhouse effect, methane from such activities as growing rice and flaring natural gas wells accounts for 20% of it. Other sources: chlorofluorocarbons (CFCs) (15%); nitrous oxide, from fertilizers and microbes (10%); and ozone (5%).

ILLUSTRATIONS BY JEAN WISENBAUGH

The company is trying to breed drought resistance into the tree varieties it will plant there. British Petroleum, which has spent $11 billion on oil and gas operations in Alaska, has a particular interest in the greenhouse problem. Drilling rigs, housing, roads, and the Trans-Alaska Pipeline are all built on permafrost, which could start to thaw in a warming trend. BP has followed the scientific debate about the greenhouse effect, but at this point believes its investment is safe. The reason: BP's facilities rest on gravel pads that insulate the permafrost beneath them.

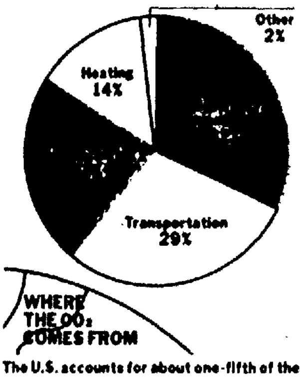
Both Alaska and Siberia have warmed up about 2.7° in just the past 20 years, according to researchers at the University of East Anglia in England. Says Michael Kelly, a climate researcher at the university and a consultant to BP: "We've now started to warn British Petroleum that 30 years out, greenhouse warming may have moved climate beyond the range of the conditions that have prevailed historically." BP is still studying the East Anglia warning.

WHAT FOLLOWS aren't hard and fast predictions of what will happen between the years 2030 and 2070, when carbon dioxide concentrations are expected to double from preindustrial levels. They are "plausible possibilities" suggested by computer models, as Howard Ferguson, assistant deputy minister of Canada's Atmospheric Environment Service, calls them.

Some of the most obvious effects will appear in agriculture. Through photosynthesis, plants make carbohydrates from CO_2 and water. As carbon dioxide concentrations increase, a plant's stomata, the pores through which gases and water vapor pass, need to open less to take in the same amount of CO_2, so the plant loses less water through evaporation. The upshot: The plant gets bigger.

If some crops grow faster, they could strip soil of nutrients more quickly, forcing farmers to buy more fertilizer. Food quality could deteriorate as CO_2 levels increase, because leaves may become richer in carbon and poorer in nitrogen. Insects feeding off plants stimulated by CO_2 would have to eat more to get their fill of nitrogen. Indeed, hungrier pests and damaging diseases might thrive on the greenhouse effect, forcing farmers to buy more pesticides as well.

The social and political consequences of the greenhouse effect are harder to assess. The Dust Bowl of the 1930s pushed millions of Midwesterners west to California. In the 1960s and 1970s, jobs and better weather pulled many millions from the Northeast to the Sunbelt. Says David Rind, a climate scientist with the Goddard Institute for Space Studies in New York City: "You may not get movements to the Southeast and Southwest anymore. It reaches 120° in Phoenix now. Will people still live there if it's 130°? 140°?" According to James Hansen of the Goddard Institute, the maximum temperature in Dallas could exceed 100° on something like 78



The U.S. accounts for about one-fifth of the world's CO_2 emissions, and 98% of these come from burning fossil fuels.

days a year; the current average is just 19.

If American agriculture is battered by such punishing summer days, and Soviet agriculture thrives owing to a longer and more temperate growing season, what would that do to the balance of power? "The United States could become a grain importer and the U.S.S.R. could become a grain exporter," says Roberts of NCAR. "At the very least, it would be a major economic, political, and social dislocation."

One of the most discussed—and feared—consequences of the greenhouse effect is a projected rise in sea level, resulting largely from thermal expansion. Like any other liquid, water increases in volume when heated. But most scientists believe the rise will be relatively gentle, on the order of eight to 16 inches, making it a problem mainly for countries with large populations near or below sea level, such as the Netherlands and Bangladesh.

Geographically, the greenhouse effect is likely to have its greatest impact in the high latitudes of the Northern Hemisphere, the broad band from 60° north—roughly the latitude of Anchorage and Stockholm—to the North Pole. A feedback effect accentuates global warming in the higher latitudes. Snow and ice reflect sunlight into space, keeping temperatures from rising. But as the globe warms, the floating Arctic ice cover starts to melt, leaving less snow and ice to reflect sunlight—enhancing the warming, which in turn melts more snow and ice. (In the Southern Hemisphere, sea ice will also melt. But the land-based Antarctic icecap is so massive—it averages two miles thick—that it would take centuries to thaw.)

IF THE WORLD as a whole warms 3° by midcentury, the higher northern latitudes might become 8° or more warmer in winter. If the global average rises 8°, winter temperatures in the higher latitudes could go up a torrid 19°. "The fabled Northwest Passage would be open," says Walt Roberts of NCAR. "You could sail from Tokyo to Europe in half the time." Maybe so, but British Petroleum and others are beginning to worry about the hazards of pack ice—large, flat masses of ice that predominate in the Arctic Ocean—and icebergs, glacier chunks like the one that sank the *Titanic*, that float off the coasts of Newfoundland and Nova Scotia. The icebergs would endanger ships and floating oil rigs.

The Arctic ice cover could also cause problems for the U.S. and Soviet defense establishments. The polar icecap of the Arctic Sea helps both Soviet and American nuclear submarines avoid detection. The effect would be more damaging to the U.S.S.R. Because American submarines are faster and can travel farther than their Soviet counterparts, they are less dependent on hiding places under the icecap.

The Soviet Union would nevertheless appear to benefit substantially from the greenhouse effect. A warming of 8° could add as many as 40 days to the growing season in the U.S.S.R. But a world with twice as much CO_2 in the atmosphere also means a continental interior that is considerably drier; the Soviet Union would have to spend tens of billions on irrigation to take advantage of the longer growing season.

How would the U.S. be affected commercially? Global warming would have strange effects on the Great Lakes, the busiest waterway in the world. Using a computer model that projects an 8° winter warming the Atmospheric Environment Service says the Great Lakes could be ice free 11 months of the year, vs. 8.5 months today. That's the good news. The bad news is that the region will also be drier, so companies shipping such major cargoes as iron ore, grain, coal, and limestone will see costs rise 30% or so because lower water levels will mean that deep-draft freighters can no longer navigate the lock systems.

PERHAPS the biggest agricultural impact on the U.S. would be in the Midwest, where climate researchers predict a warming drying trend. Staggering wheat crop losses deepened the Great Depression and prompted the biggest population migration in American history. When temperatures rise as little as 1.8° and precipitation drops 10%, Midwestern crops will suffer. Paul Waggoner, director of the Connecticut Agricultural Experiment Station in New Haven, sees a 2% to 5% cut in the yield of commercially desirable winter wheat.

Western Europe might escape the nastier consequences of global warming because its relatively small landmass is close to the sea and will *not* undergo the same degree of continental drying as the U.S., Canada, and the Soviet Union. What will happen to European temperatures is being debated. Most scientists think the Gulf Stream, flowing thousands of miles from the Caribbean, should continue to keep Western Europe from freezing to the consistency of Newfoundland, which is at the same latitude. But Wallace Broecker of Columbia University's Lamont-Doherty Geological Observatory in Palisades, New York, warns that the greenhouse effect could disturb the global circulation of the oceans in ways that cannot be predicted. Like a teakettle that doesn't boil the moment it's switched on, the earth's oceans, which range up to seven miles deep, take time to warm up. It could take 20 to 60 years before the oceans show the full effect of global warming.

Research on the effects of global warming in countries of the Third World and the Southern Hemisphere is sketchier. Africa may benefit, at least in rainfall. The rain belt across the equator would move northward, according to research about to be published by Syukuro Manabe, a climate modeler at Princeton's Geophysical Fluid Dynamics Laboratory. That's good news for the parched nations of the Sahel, including Chad, Sudan, and Ethiopia, which have suffered this century's deadliest droughts. Marginal farmland in central China may get more rainfall, increasing crop yields. India and especially Bangladesh, a third of which is only 20 feet above sea level on average, would be battered by more storms and flooding.

"When climate changes," a United Nations Environment Program (UNEP) report bluntly declared last year, "society suffers." So what should we do?

Clearly there are things we can't do. We can't scrub carbon dioxide out of industrial emissions the way we can pollutants like sulfur dioxide. So-called chemically alkaline absorbent systems that soak up CO_2 emissions add as much as 80% to the cost of producing electricity. The most efficient CO_2 scrubbers are trees. Like other plants they absorb CO_2, using it to make food and build wood. But trees are being felled around the world at a clip of 50 acres a minute, mostly in Brazil, West Africa, and Indonesia, according to UNEP. Reducing deforestation would help, but reforestation, proposed occasionally, isn't a practical answer. The Oak Ridge National Laboratory in Tennessee estimates that to stop the greenhouse effect cold would take 1.7 billion acres of sycamore trees, which are especially good at soaking up CO_2. That's an area roughly the size of Australia.

In a sense, getting up in the morning adds to the greenhouse effect. Everyone contributes. If everyone is to blame, no one is to blame.

Changing the mix of fossil fuels can help. Natural gas produces half the CO_2 of coal and about two-thirds that of oil for the same amount of energy. While it's unlikely to happen, shifting completely to natural gas from coal or petroleum could extend by 20 to 30 years the time it takes for atmospheric CO_2 to double from preindustrial levels.

Some help should come from a 1987 treaty curbing production of chlorofluorocarbons. Released into the atmosphere, these synthetic chemicals, used in industrial solvents and refrigerants, eat away at the atmospheric ozone layer that protects people from dangerous solar radiation, which can cause skin cancer and cataracts. If the signatories comply, CFC production would be limited to 1986 levels beginning next year and gradually drop 50% by 1999.

Unfortunately, the CFC agreement is not a model for curtailing carbon dioxide. In that case a single industry was the source of the problem; there was someone to blame. Once persuaded by strong scientific evidence, the chemical industry agreed to institute production curbs. By contrast, no one controls the production of carbon dioxide. It is a result of everyday processes of life. In a sense, getting up in the morning adds to the greenhouse effect. Turning on the bathroom light uses electricity generated by fossil fuels; driving to work burns gasoline; even the building you work in may have added to the problem because making concrete gives off CO_2. Everyone contributes to the greenhouse effect. If everyone is to blame, no one is to blame.

Energy conservation would reduce carbon dioxide emissions at the source, but would be tough to enforce. Most alternative energy sources seem impractical, for the moment. Wind, geothermal, and solar energy have so far been casualties of low oil prices. So have synfuels, which have the added disadvantage of producing as much carbon dioxide as fossil fuels. Nuclear energy, despite well-deserved public concern about its safety, may deserve a second look because it produces no carbon dioxide.

ALL THESE strategies seek to buy time. Obviously it is better to adjust to the greenhouse effect over 200 years rather than 50. But an all-out international effort to reduce CO_2 emissions seems sure to hit two major snags. Countries that stand to benefit from global warming aren't likely to bring much enthusiasm to averting it. And those that stand to lose have trouble viewing this distant, somewhat speculative threat with the urgency required to call forth expensive and disruptive countermeasures.

If nations don't take action, Mick Kelly of the University of East Anglia suggests what businesses might do. "The winners from global warming," he says, "are going to be those people who think ahead of time and plan. The losers are going to be those who respond only when the crisis arrives, on the spur of the moment." For those who want to come out winners, now is not too soon to start thinking. ■

WHAT MAKES THE WEATHER SO HARD TO FORECAST

How do climate scientists know the greenhouse effect will bring about the woes that they predict? They don't know to a total certainty. What they *do* know is based on half a dozen high-powered computer simulation programs, called general circulation models, in North America and Europe. Researchers feed in equations based on the laws of physics, along with assumptions about clouds, sea ice, ocean currents, soil moisture, atmospheric convection, and emission of heat from the ground.

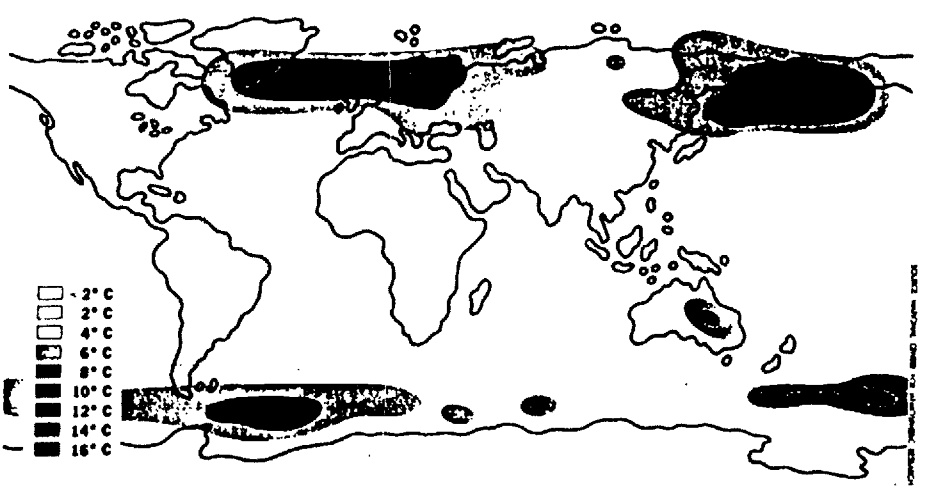
More complicated things happen in the heavens and on earth, however, than are dreamt of in the equations of scientists. Even using the best supercomputers, none of the models is so good that it can start with known weather conditions at a given point in the past and reproduce precisely what has happened since. To make the calculations manageable even by computers, most of the models suppose either that the oceans are a shallow, motionless swamp or that they don't exist at all. Despite that oversimplification, an especially sophisticated computer model at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, requires 1.5 trillion calculations to advance its predictions a single day.

One basic problem is called grid resolution. Climatologists divide the world into a grid. Most use a grid with squares the size of France. The grid defines France as a single set of numbers, failing to distinguish the cool, rainy north from the sunny, drier south. In his 1987 book *Chaos*, James Gleick, a New York *Times* reporter, imagined a world covered with a vast jungle gym of sensors spaced a foot apart and rising 35 miles to the top of the atmosphere. Each sensor measures with great precision temperature, pressure, humidity, and every other meteorological variable. An infinitely powerful computer processes all the data. This seemingly perfect monitoring system still could not predict exactly the weather next month in Atlanta.

The reason: The computer would not detect microfluctuations that took place in between the sensors. Errors multiply so quickly that within hours the reality of weather diverges from its predicted course. In effect, you can never have enough grid squares to forecast weather accurately. Tiny variations matter. The Butterfly Effect, known technically as "sensitive dependence on initial conditions," gets its name from the thought that a butterfly flapping its wings today in Nagasaki could conceivably influence storms next month in New York.

While most scientists agree that the greenhouse effect is coming, there aren't enough data yet to say with absolute conviction what its consequences will be. Certainties in science are a long time in the making. In a profession where tentative conclusions require decades' worth of data, one swallow does not make a summer. As recently as the 1970s some climatologists were worrying about global *cooling*, because world temperatures had peaked in the 1940s and then declined into the 1970s. Air pollutants such as volcanic and man-made dust may have blocked enough sunlight to lower global temperatures.

This computer model shows possible rises in winter temperatures, in Celsius, if CO_2 in the air doubles from the 18th-century level.



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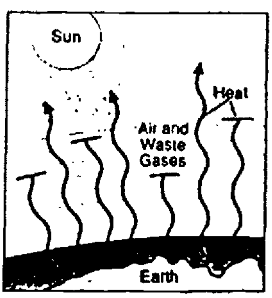
The Greenhouse Effect? Real Enough.

A fierce drought is shriveling crops from Texas to North Dakota and has shrunk the Mississippi to its lowest levels on record. Dry years are part of nature's cycle. Still, it's time to take seriously another possible influence — the warming of the atmosphere by waste gases from a century of industrial activity. Whether or not the feared greenhouse effect is real, there are several preventive measures worth taking in their own right.

The greenhouse theory holds that certain waste gases let in sunlight but trap heat, which otherwise would escape into space. Carbon dioxide has been steadily building up through the burning of coal and oil — and because forests, which absorb the gas, are fast being destroyed. There is no clear proof that the gases have yet begun to warm the atmosphere. But there's circumstantial evidence, and some experts think it is getting stronger.



For example, four of the last eight years — 1980, 1981, 1983 and 1987 — have been the warmest since measurements of global surface temperatures began a century ago, and 1988 may be another record hot year. Still, there have been hot spells before, followed by a cooling.

According to computer simulations of the world's climate, there should be more rain in a greenhouse-heated globe. The rain falls in different places: more at the poles and the equator, less in the mid-latitudes. The drought in the Middle West falls in with these projections. But it stops far short of proving that the greenhouse effect has begun. "As far as we can tell, this is a tough summer well within the normal range of variability," says Donald Gilman, the Weather Service's long-range forecaster.

That's the nub of the problem: It's hard to identify a small, gradual sign of global warming amid wide natural fluctuations in climate. Even over the long term, the evidence is merely indicative. The world has warmed half a degree centigrade over the last century. But the warming is less than some computer models predict, forcing defenders of the greenhouse theory to argue that the extra heat is disappearing into the oceans.

With the greenhouse effect still uncertain, why take preventive steps, especially since the main one, burning less coal, would be enormously expensive? One answer is that it may take years to acquire positive proof of greenhouse-induced climate change, and the longer society waits, the larger a warming it will have to adapt to if the greenhouse theory turns out to be valid. Even a small warming could produce violent changes in climate. At worst, the Gulf Stream might shift course, failing to warm Europe. Sea level could rise 20 feet if the West Antarctic Ice Cap melts, flooding coastal cities from New York to New Orleans.

Several measures to slow the greenhouse warming are worth taking for other reasons:

□ Cut production of freons, chemicals used as solvents and refrigerants. Important greenhouse gases, they destroy the life-protecting ozone layer.

□ Protect tropical forests, which not only absorb carbon dioxide but also nourish a rich variety of animal and plant life.

□ Encourage conservation of energy and use of natural gas, which produces half as much carbon dioxide as does coal.

□ Develop cheaper, safer nuclear power; nuclear plants produce no carbon dioxide or acid rain.

Many climatologists expect that the greenhouse theory will eventually prove true, but fear to issue alarmist warnings ahead of time. Their caution is justified. But there's an ample case for taking these initial preventive measures when the cost of such insurance is so low and the discomforts of abrupt climate change, as the drought demonstrates, so high.

Senator WIRTH. Senator Ford.

Senator FORD. No. Thank you, Mr. Chairman. I look forward to being educated.

Senator WIRTH. Thank you.

Senator Conrad.

STATEMENT OF HON. KENT CONRAD, U.S. SENATOR FROM NORTH DAKOTA

Senator CONRAD. Well, I would just briefly say, Mr. Chairman, that I come from a state that is being devastated by the current drought. I was just there this weekend, and the pastures looked like a moonscape. The wheat crop is absolutely devastated. And we have been through this before.

In the 1930's we had a similar drought, and I will be very interested in hearing what evidence there might be to indicate that the drought of the 1980's is different than the drought of the 1930's. I think that really is the central question before us, to establish the record and the case for an increase over time of temperature and what the long-term effects might be. And that's what I will be looking for in this hearing.

And I want to thank both Senator Wirth for his leadership on this issue and the Chairman of the full committee for his support of having a hearing like this. It is terribly important to an area like mine that is so commodity dependent.

Senator WIRTH. Thank you, Senator Conrad.

We are joined today and in this effort by Senator Max Baucus, who along with many members of the Committee on Environment and Public Works, has had a great concern about this and related kinds of issues. Max, delighted to have you here.

STATEMENT OF HON. MAX BAUCUS, U.S. SENATOR FROM MONTANA

Senator BAUCUS. Thank you, Mr. Chairman.

Mr. Chairman, I commend you and Senator Johnston for holding these hearings. The more hearings we have in more committees and not get hung up on committee jurisdiction, the better off we're going to be and the more likely it is we will find a meaningful solution to the problem.

I sense that we are experiencing a major shift. It's a like of shift of tectonic plates. Our country not too many years ago was concerned basically with economic and environmental problems within the borders of our country. And a few years ago we began to realize that we are economically interdependent with other countries, other peoples, other industries around the world, and our fate is very much tied up with the economic fate of people in other countries.

I think there is another shift now, and it's an environmental tectonic plate shift. That is, we realize as Americans that our environmental problems in America—the focus must be not only on our own country within the confines of our borders, but also the environmental problems worldwide. The world is getting smaller. We all are in this boat together. And I think that this hearing and others like it help that awareness.

In addition, Mr. Chairman, I have a sense of deja vu. It wasn't too long ago that scientists predicted with their models the depletion of ozone in the stratosphere. We looked at those models in other committees, and what we found is that the models were not accurate, but they were timid. They did not really predict the degree to which stratospheric ozone is depleting. They did not predict the degree to which the Antarctic hole has developed. They did not predict the degree to which ozone depletion is not in the stratosphere over the Antarctic, but also now over northern hemispheres.

So, I suggest that if we err here, we do err on the side of action. I think that the scientific models are becoming more sophisticated. They are becoming more accurate. And the old question of, well, do we have enough information, let's take some more time, I think it becoming more clear not only because of what has happened with the depletion of stratospheric ozone, but because the models and scientific analysis is becoming more sophisticated and more accurate that we can be more assured and more confident of moving forward more quickly.

I've had a chance to briefly look at Mr. Jim Hansen's testimony, and I think that his testimony is quite graphic in predicting that this is not just a chance occurrence, that statistically the increase in global temperature is not only in our country, but in Moscow in the Soviet Union and other similar latitudes. It is beyond chance. It is more certain as the predictions are greater that, in fact, the earth is warming up to the degree that the models tend to predict.

The answers I think are to inventory our carbon dioxide and other greenhouse gas sources. We have to get a better idea of what the major sources are of the various greenhouse gases. Certainly one source is the automobile industry, automobiles. Certainly a cause of the problem is our energy inefficiency in our country. We are one of the most energy inefficient countries in the world. And we're going to have to bite the bullet frankly, with the automobile industry and other major industries to force ourselves to be more efficient and reduce greenhouse gas emissions. CFC reductions help. That is only a small part of the problem. There are the methanes. There are carbon dioxide and other gases that have to be addressed.

And I very much commend you, Mr. Chairman, for taking this action.

[The prepared statement of Senator Baucus follows:]

STATEMENT BY SENATOR MAX BAUCUS ON GLOBAL WARMING

I am delighted to have the opportunity this afternoon to testify before the Subcommittee in this hearing on global climate change. The greenhouse effect, global climate change, and stratospheric ozone depletion are interrelated environmental problems which pose the greatest environmental challenge that our planet will face in the next decade.

I commend you, Mr. Chairman, for holding this hearing and for your continued interest in the greenhouse effect and global climate change. It is an interest we share. Since December of 1985, members of the Committee on Environment and Public Works have held nine days of hearings on these issues.

Testimony presented at those hearings by leading scientists painted a disturbing picture. Like those who believe the stock market crash of October was a warning on the economy, we must ask ourselves if the drought we are facing is nature's warning to mankind to clean up its act.

Dr. Wallace Broecker described the problem we face this way:

"The inhabitants of planet Earth are quietly conducting a gigantic environmental experiment. So vast and so sweeping will be its impact that, were it brought before any responsible council for approval, it would be firmly rejected as having potentially dangerous consequences. Yet the experiment goes on with no significant interference from any jurisdiction or nation."

The experiment in question is the so-called greenhouse effect - the gradual warming of our atmosphere caused by an overload of carbon dioxide and other trace gases.

I like to think greenhouses produce useful things for mankind. However, a global greenhouse will produce very little except more drought, famine, and economic and social upheaval.

The warning signs are clear. Carbon dioxide concentrations have increased by 25% since 1900. Methane concentrations have risen about 100% in the last 150 years.

In the last 35 years alone there has been a 30 to 40% increase. The two principal fluorocarbons implicated in the greenhouse effect - CFC-11 and CFC-12 - are growing at a rate of 5% per year. Nitrous oxide concentrations are growing at two- tenths of one percent per year. Tropospheric ozone is increasing by 1% per year in the Northern Hemisphere. Elsewhere on the globe, tropospheric ozone trends are not well known.

The excess radiation absorbed by these greenhouse gases provides the energy to drive the climate system and alter global and regional climate patterns, atmospheric circulation patterns, and oceanic circulation patterns.

The projected increases in the greenhouse gases are predicted to cause unprecedented global and regional climate changes.

Temperature will increase. Current models predict an increase in the average global temperature of 1.5 to 4.5 degrees centigrade by the year 2030. That is an increase of about 3 to 9 degrees Fahrenheit in only 40 years.

These "global average temperatures" do not accurately reflect local temperature changes. An average temperature rise of only three degrees centigrade could mean an increase of more than ten degrees centigrade at high altitudes in some seasons.

Precipitation will increase. A warmer climate will evaporate more moisture which will ultimately fall to the ground as precipitation. Hence, overall, the globe will be wetter and more humid.

Precipitation patterns will change, possibly upsetting agricultural activities worldwide.

A warmer atmosphere will melt the sea ice in the polar regions. Since the underlying ocean is much darker than the sea ice, melting of the ice will lead to increased solar absorption. This absorption will act as a feedback mechanism for further ocean and atmosphere circulation changes.

Current models predict that climate change will lead to the dessication of the continents in the mid-latitudes. In summer, the Great Plains of the United States, Central Europe, and parts of the Soviet Union could experience Dust Bowl conditions.

Sea level could rise from one to four feet, inundating our coastlines and contaminating drinking water supplies with salt water.

Ocean currents could shift, changing the climate of many areas and disrupting fisheries.

The frequency of tropical storms is predicted to increase, as is increased monsoonal rain in the tropics.

With the "greenhouse effect", we are not talking about short-term changes. We are talking about permanent and perhaps ongoing change for some indefinite period into the future.

We are talking about a situation where mankind has finally wrestled control of this planet from Nature. It is a responsibility we are ill equipped to assume.

We are already committed to some of these changes. Past emissions of greenhouse gases have already committed Earth to warm by 0.5 to 1.5 degrees centigrade over the pre-industrial era. If emissions continue along their present track, we will have committed Earth to a warming of 1.5 to 4.5 degrees centigrade by 2030.

These changes may be occurring now. It is expected that within the next few years, we shall actually be able to measure these changes.

The nation is in the midst of one of the most devastating droughts since the dust bowl days of the 30's. Drought is occurring from California to Texas to Georgia to Iowa to Montana.

Last week I accompanied a group of Senators to view the problems posed by drought in the Northern Great Plains. I can tell you things are pretty grim in Montana.

Our reservoirs did not fill this Spring. Estimates of wheat production show yields are down as much as fifty percent. In a short period of time, without rain, we can expect major problems with grasshoppers ravaging what crops remain.

Over the past few years, the West has experienced devastating forest fires. The fire season started over a month earlier than usual in Southern California.

The current drought is responsible for real economic suffering.

If the climate has changed due to greenhouse gases, we will be forced to live with these changes and to adapt.

As policy-makers, we must find ways to minimize economic dislocations on the one hand. On the other hand, we must minimize the rate of climate change to one we can adapt to.

The fundamental question is, should we wait until the problem is actually known for sure, or take steps to address the problem now?

I believe we need to move now. We are talking about a problem that has been building up for at least the last century. Each day we fail to set needed policies in motion, the potential for failure increases.

The fundamental issue that we face is to develop a strategy to deal with global climate change. The next decade should be a period of intense scientific research designed to provide answers to the greenhouse problem, policy exploration, and adoption of appropriate preventative and adaptive control measures.

There are things which we can do now. Reductions in the use of coal and gas, and energy conservation measures will reduce the concentrations of greenhouse gases.

Reductions in the emissions of chlorofluorocarbons will help to slow the rate of climate change, and will help to preserve the Earth's stratospheric ozone shield. Both Senator Chafee and I have introduced legislation which would eventually phase-out the use of harmful man-made CFC's which are currently destroying the Earth's protective ozone layer.

The problem of global warming and ozone depletion have reached a stage that requires a broader and more institutional commitment to international dialogue. The focus for this effort should be the United Nations Environment Program (UNEP).

We need to urge UNEP to step forward with a comprehensive report on global climate change, detailing the seriousness of the problem for all nations of the world. This effort could play a pivotal role in developing an international committment to address this problem.

Finally we need to focus the efforts of the scientific community on improving our understanding of the interrelated problems of the greenhouse effect, global climate change, and stratospheric ozone depletion. We need to set the "Greenhouse Effect" as the number one priority of the International Geosphere/Biosphere Program, and set priorities for our research efforts.

We are at a point in time where we must examine the policy options now. Some changes in climate as we know it are already in the bank. The magnitude and timing of other changes are still speculative. We must ensure that the scientific research which is started today is designed to improve the information base for policy options.

I think it would be useful to spell out some of the means that will have to be considered in order to limit climate change and thus stabilize or reduce the concentration of greenhouse gases in the atmosphere.

We know, for example, that we must reduce the emission of carbon dioxide which makes up about one half of the greenhouse emissions. What method should the Secretary of State and the Administrator of EPA consider in this regard? Recent Senate testimony has suggested a number of policies which will have to be considered in order for the United States to reduce its carbon dioxide emissions which account for almost a quarter of the global total.

Carbon dioxide emissions are tied to the types and amounts of fossil fuels which we use in our economy. Therefore, controlling carbon dioxide emissions will require changes in the way we manage our energy use in the future. Consideration should be given to improvement in energy end-use efficiency, such as lighting, and across the board in new appliances. The efficiency of supply energy technology can also be improved

New gas-fueled power plant technologies appear to improve efficiency substantially. A vast improvement of auto efficiency standards for cars sold in the United States must be considered in order to lower the use of gasoline.

Pricing initiatives must be considered in order to reflect the "externalities" in the price of fossil fuels. A number of experts have suggested the establishment of a carbon dioxide tax in order to reflect the damage to our climate reflected in the price of energy.

Fuel switching must also be considered since some fuels produce much less carbon dioxide per BTU than others. Coal, for example, produces twice the carbon dioxide per BTU as gas.

Stopping the destruction of tropical forests - a significant carbon dioxide sink - is an important step. Consideration should also be given to reforestation.

We know also that the complete elimination of CFCs would provide a major greenhouse benefit. That too should be considered.

We know that improving the controls on carbon monoxide might control the buildup of methane.

We should consider reexamining whether nitrous oxides can be controlled through air pollution control technologies. We may need to control the buildup of tropospheric ozone not just locally, but also on a national basis because ozone in the troposphere is also a greenhouse gas.

Dealing with the greenhouse problem is a daunting task. We must not wait; we must begin now. We are already too late. I think the list of responses I mentioned previously should help us get started in formulating and initiating a response.

There is an urgent need to move rapidly towards the development of policies to control and mitigate the impacts of global climate change, both domestically and internationally.

I look forward to working with you to ensure that the United States is prepared to meet the threat of global climate change. I am hopeful that your discussions today will begin to focus our attention on the development of policies to combat global climate change.

I appreciate the opportunity to appear before you today to discuss the major environmental problem facing our planet, global climate change.

Senator WIRTH. Thank you, Senator Baucus.
Senator Bumpers.

STATEMENT OF HON. DALE BUMPERS, U.S. SENATOR FROM ARKANSAS

Senator BUMPERS. Well, Mr. Chairman, I won't burden our time constraints here except to say I welcome all of our witnesses here today. Bill Moomaw, who was a congressional science fellow with me when, Bill? In 1976?

Dr. MOOMAW. Yes.

Senator BUMPERS. In 1976, and is the person that is responsible for my deep and abiding interest in both the ozone problem and the greenhouse theory of Dr. Ramanathan, all of which those of us who were born to rule knew back in 1976 was a problem.

But we couldn't get one camera—I see we have three cameras here today—for the hearings we held back then. We had nine hearings and had the best atmospheric scientists in the country. Every one of them told us that we were possibly facing a cataclysm in both of these areas.

And now we know that the four warmest years in the last 130 years—the four hottest years of the last 130 years—have occurred since 1980. Now, that may be pure coincidence, but my belief is that we cannot afford to assume that. On the contrary, we have to assume the very opposite that we may be facing a cataclysm in the future, much of which is already in place and irreversible. But that doesn't excuse us from the obligation to take very dramatic action. None of us is quite action to take yet.

And Dr. Hansen is going to testify today to what I just said plus some additional things that ought to be cause for headlines in every newspaper in America tomorrow morning because, after all, we're going to have to have a lot of political support for this. Nobody wants to take on the automobile industry. Nobody wants to take on any of the industries that produce the things that we throw up into the atmosphere. They don't want that stopped, and that's understandable. But what you have are all these competing economic interests pitted against our very survival.

Thank you, Mr. Chairman.

Senator WIRTH. Thank you very much, Senator Bumpers.

Before we begin, there are about eight or nine seats down here. Maybe those of you who are standing up behind the table over here might want to come down. There is no point in standing up through this on a hot day or any day.

Thank you all. I'm delighted to have with us such a distinguished group of witnesses.

What I would like to do, if we might, today is to start with Dr. James Hansen, the Director of the Goddard Institute for Space Studies, whose climate data have demonstrated what Senator Bumpers was pointing out, the four warmest years during this decade, and who I believe has a number of other interesting revelations from recent research that might set the scene for this afternoon's discussion. If we could then move to Dr. Michael Oppenheimer, Senior Scientist with the Environmental Defense Fund; and Dr. George Woodwell, Director of the Woods Hole Research

Center in Woods Hole; Dr. Manabe from NOAA, Geophysical Fluid Dynamics Laboratory in Princeton; Dr. Dudek, a senior economist with the EDF; and finally Dr. William Moomaw, Senior Associate of WRI, World Resources Institute.

All of your statements will be included in full in the record, and we would ask you to summarize in the way that you think would be most beneficial. And after you have all had a chance to testify, we will then go to questions and discussions with the members of the Senate. So, gentlemen, thank you very much for being here. Dr. Hansen, if you would start us off, we'd appreciate it.

STATEMENT OF DR. JAMES HANSEN, DIRECTOR, NASA GODDARD INSTITUTE FOR SPACE STUDIES

Dr. HANSEN. Mr. Chairman and committee members, thank you for the opportunity to present the results of my research on the greenhouse effect which has been carried out with my colleagues at the NASA Goddard Institute for Space Studies.

I would like to draw three main conclusions. Number one, the earth is warmer in 1988 than at any time in the history of instrumental measurements. Number two, the global warming is now large enough that we can ascribe with a high degree of confidence a cause and effect relationship to the greenhouse effect. And number three, our computer climate simulations indicate that the greenhouse effect is already large enough to begin to effect the probability of extreme events such as summer heat waves.

My first viewgraph, which I would like to ask Suki to put up if he would, shows the global temperature over the period of instrumental records which is about 100 years. The present temperature is the highest in the period of record. The rate of warming in the past 25 years, as you can see on the right, is the highest on record. The four warmest years, as the Senator mentioned, have all been in the 1980s. And 1988 so far is so much warmer than 1987, that barring a remarkable and improbable cooling, 1988 will be the warmest year on the record.

Now let me turn to my second point which is causal association of the greenhouse effect and the global warming. Causal association requires first that the warming be larger than natural climate variability and, second, that the magnitude and nature of the warming be consistent with the greenhouse mechanism. These points are both addressed on my second viewgraph. The observed warming during the past 30 years, which is the period when we have accurate measurements of atmospheric composition, is shown by the heavy black line in this graph. The warming is almost 0.4 degrees Centigrade by 1987 relative to climatology, which is defined as the 30 year mean, 1950 to 1980 and, in fact, the warming is more than 0.4 degrees Centigrade in 1988. The probability of a chance warming of that magnitude is about 1 percent. So, with 99 percent confidence we can state that the warming during this time period is a real warming trend.

The other curves in this figure are the results of global climate model calculations for three scenarios of atmospheric trace gas growth. We have considered several scenarios because there are uncertainties in the exact trace gas growth in the past and especially in the future. We have considered cases ranging from business as usual, which is scenario A, to draconian emission cuts, scenario C, which would totally eliminate net trace gas growth by year 2000.

The main point to be made here is that the expected global warming is of the same magnitude as the observed warming. Since there is only a 1 percent chance of an accidental warming of this magnitude, the agreement with the expected greenhouse effect is of considerable significance. Moreover, if you look at the next level of detail in the global temperature change, there are clear signs of the greenhouse effect. Observational data suggests a cooling in the stratosphere while the ground is warming. The data suggest somewhat more warming over land and sea ice regions than over open ocean, more warming at high latitudes than at low latitudes, and more warming in the winter than in the summer. In all of these cases, the signal is at best just beginning to emerge, and we need more data. Some of these details, such as the northern hemisphere high latitude temperature trends, do not look exactly like the greenhouse effect, but that is expected. There are certainly other climate change factors involved in addition to the greenhouse effect.

Altogether the evidence that the earth is warming by an amount which is too large to be a chance fluctuation and the similarity of the warming to that expected from the greenhouse effect represents a very strong case. In my opinion, that the greenhouse effect has been detected, and it is changing our climate now.

Then my third point. Finally, I would like to address the question of whether the greenhouse effect is already large enough to affect the probability of extreme events, such as summer heat waves. As shown in my next viewgraph, we have used the temperature changes computed in our global climate model to estimate the impact of the greenhouse effect on the frequency of hot summers in Washington, D.C. and Omaha, Nebraska. A hot summer is defined as the hottest one-third of the summers in the 1950 to 1980 period, which is the period the Weather Bureau uses for defining climatology. So, in that period the probability of having a hot summer was 33 percent, but by the 1990s, you can see that the greenhouse effect has increased the probability of a hot summer to somewhere between 55 and 70 percent in Washington according to our climate model simulations. In the late 1980s, the probability of a hot summer would be somewhat less than that. You can interpolate to a value of something like 40 to 60 percent.

I believe that this change in the frequency of hot summers is large enough to be noticeable to the average person. So, we have already reached a point that the greenhouse effect is important. It may also have important implications other than for creature comfort.

My last viewgraph shows global maps of temperature anomalies for a particular month, July, for several different years between 1986 and 2029, as computed with our global climate model for the intermediate trace gas scenario B. As shown by the graphs on the left where yellow and red colors represent areas that are warmer than climatology and blue areas represent areas that are colder than climatology, at the present time in the 1980s the greenhouse warming is smaller than the natural variability of the local temperature. So, in any given month, there is almost as much area that is cooler than normal as there is area warmer than normal. A few decades in the future, as shown on the right, it is warm almost everywhere.

However, the point that I would like to make is that in the late 1980's and in the 1990's we notice a clear tendency in our model for greater than average warming in the southeast United States and the midwest. In our model this result seems to arise because the Atlantic Ocean off the coast of the United States warms more slowly than the land. This leads to high pressure along the east coast and circulation of warm air north into the midwest or the southeast. There is only a tendency for this phenomenon. It is certainly not going to happen every year, and climate models are certainly an imperfect tool at this time. However, we conclude that there is evidence that the greenhouse effect increases the likelihood of heat wave drought situations in the southeast and midwest United Stats even though we cannot blame a specific drought on the greenhouse effect.

Therefore, I believe that it is not a good idea to use the period 1950 to 1980 for which climatology is normally defined as an indication of how frequently droughts will occur in the future. If our model is approximately correct, such situations may be more common in the next 10 to 15 years than they were in the period 1950 to 1980.

Finally, I would like to stress that there is a need for improving these global climate models, and there is a need for global observations if we're going to obtain a full understanding of these phenomena.

That concludes my statement, and I'd be glad to answer questions if you'd like.

[The prepared statement of Dr. Hansen follows:]

THE GREENHOUSE EFFECT: IMPACTS ON CURRENT GLOBAL TEMPERATURE AND REGIONAL HEAT WAVES

STATEMENT OF

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PRESENTED TO:

United States Senate

Committee on Energy and Natural Resources

June 23, 1988

PREFACE

This statement is based largely on recent studies carried out with my colleagues S. Labedeff, D. Rind, I. Fung, A. Lacis, R. Ruedy, G. Russell and P. Stone at the NASA Goddard Institute for Space Studies.

My principal conclusions are: (1) the earth is warmer in 1988 than at any time in the history of instrumental measurements, (2) the global warming is now sufficiently large that we can ascribe with a high degree of confidence a cause and effect relationship to the greenhouse effect, and (3) in our computer climate simulations the greenhouse effect now is already large enough to begin to affect the probability of occurrence of extreme events such as summer heat waves; the model results imply that heat wave/drought occurrences in the Southeast and Midwest United States may be more frequent in the next decade than in climatological (1950-1980) statistics.

1. Current global temperatures

Present global temperatures are the highest in the period of instrumental records, as shown in Fig. 1. The rate of global warming in the past two decades is higher than at any earlier time in the record. The four warmest years in the past century all have occurred in the 1980's.

The global temperature in 1988 up to June 1 is substantially warmer than the like period in any previous year in the record. This is illustrated in Fig. 2, which shows seasonal temperature anomalies for the past few decades. The most recent two seasons (Dec.-Jan.-Feb. and Mar.-Apr.-May, 1988) are the warmest in the entire record. The first five months of 1988 are so warm globally that we conclude that 1988 will be the warmest year on record unless there is a remarkable, improbable cooling in the remainder of the year.

2. Relationship of global warming and greenhouse effect

Causal association of current global warming with the greenhouse effect requires determination that (1) the warming is larger than natural climate variability, and (2) the magnitude and nature of the warming is consistent with the greenhouse warming mechanism. Both of these issues are addressed quantitatively in Fig. 3, which compares recent observed global temperature change with climate model simulations of temperature changes expected to result from the greenhouse effect.

The present observed global warming is close to 0.4°C, relative to 'climatology', which is defined as the thirty year (1951-1980) mean. A warming of 0.4°C is three times larger than the standard deviation of annual mean temperatures in the 30-year climatology. The standard deviation of 0.13°C is a typical amount by which the global temperature fluctuates annually about its 30 year mean; the probability of a chance warming of three standard deviations is about 1%. Thus we can state with about 99% confidence that current temperatures represent a real warming trend rather than a chance fluctuation over the 30 year period.

We have made computer simulations of the greenhouse effect for the period since 1958, when atmospheric CO_2 began to be measured accurately. A range of trace gas scenarios is considered so as to account for moderate uncertainties in trace gas histories and larger uncertainties in future trace gas growth rates. The nature of the numerical climate model used for these simulations is described in attachment A (reference 1). There are major uncertainties in the model, which arise especielly from assumptions about (1) global climate sensitivity and (2) heat uptake and transport by the ocean, as discussed in attachment A. However, the magnitude of temperature changes computed with our climate model in various test cases is generally consistent with a body of empirical evidence (reference 2) and with sensitivities of other climate models (reference 1).

The global temperature change simulated by the model yields a warming over the past 30 years similar in magnitude to the observed warming (Fig. 3). In both the observations and model the warming is close to 0.4°C by 1987, which is the 99% confidence level.

It is important to compare the spatial distribution of observed temperature changes with computer model simulations of the greenhouse effect, and also to search for other globel changes related to the greenhouse effect, for example, changes in ocean heat content and sea ice coverage. As yet, it is difficult to obtain definitive conclusions from such comparisons, in part because the natural variability of regional temperatures is much larger then that of global mean temperature. However, the climate model simulations indicate that certain gross characteristics of the greenhouse warming should begin to appear soon, for example, somewhat greater warming at high latitudes than at low latitudes, greater warming over continents than over oceans, end cooling in the stratosphere while the troposphere warms. Indeed, observations contain evidence for all these characteristics, but much more study and improved records are needed to establish the significance of trends and to use the spatial information to understand better the greenhouse effect. Analyses must account for the fact that there are climate change mechenisms at work, besides the greenhouse effect; other anthropogenic effects, such as changes in surface albedo and tropospheric aerosols, are likely to be especially important in the Northern Hemisphere.

We can also examine the greenhouse warming over the full period for which global temperature change has been measured, which is approximately the past 100 years. On such a longer period the natural variability of global temperature is larger; the standard deviation of global temperature for the past century is 0.2°C. The observed warming over the past century is about 0.6-0.7°C. Simulated greenhouse warming for the past century is in the range 0.5°-1.0°C, depending upon various modeling assumptions (e.g., reference 2). Thus, although there are greater uncertainties about climate forcings in the past century than in the past 30 years, the observed and simulated greenhouse warmings are consistent on both of these time scales.

Conclusion. Global warming has reached a level such that we can ascribe with a high degree of confidence a cause and effect relationship between the greenhouse effect and the observed warming. Certainly further study of this issue must be made. The detection of a global greenhouse signal represents only a first step in analysis of the phenomenon.

3. Greenhouse impacts on summer heat waves

Global climate models are not yet sufficiently realistic to provide reliable predictions of the impact of greenhouse warming on detailed regional climate patterns. However, it is useful to make initial studies with state-of-the-art climate models; the results can be examined to see whether there are regional climate change predictions which can be related to plausible physical mechanisms. At the very least, such studies help focus the work needed to develop improved climate models and to analyze observed climate change.

One predicted regional climate change which has emerged in such climate model studies of the greenhouse effect is a tendency for mid-latitude continental drying in the summer (references 3,4,5). Dr. Manabe will address this important issue in his testimony today. Most of these studies have been for the case of doubled atmospheric CO_2, a condition which may occur by the middle of next century.

Our studies during the past several years at the Goddard Institute for Space Studies have focused on the expected transient climate change during the next few decades, as described in the attachment to my testimony. Typical results from our simulation for trace gas scenario B are illustrated in Fig. 4, which shows computed July temperature anomalies in several years between 1986 and 2029. In the 1980's the global warming is small compared to the natural variability of local monthly mean temperatures; thus the area with cool temperatures in a given July is almost as great as the area with warm temperatures. However, within about a decade the area with above normal temperatures becomes much larger than the area with cooler temperatures.

The specific temperature patterns for any given month and year should not be viewed as predictions for that specific time, because they depend upon unpredictable weather fluctuations. However, characteristics which tend to repeat warrant further study, especially if they occur for different trace gas scenarios. We find a tendency in our simulations of the late 1980's and the 1990's for greater than average warming in the Southeast and Midwest United States, as illustrated in Attachment A and in Fig. 4. These areas of high temperature are usually accompanied by below normal precipitation.

Examination of the changes in sea level pressure and atmospheric winds in the model suggests that the tendency for larger than normal warming in the Midwest and Southeast is related to the ocean's response time; the relatively slow warming of surface waters in the mid-Atlantic off the Eastern United States and in the Pacific off California tends to increase sea level pressure in those ocean regions and this in turn tends to cause more southerly winds in the eastern United States and more northerly winds in the western United States. However, the tendency is too small to be apparent every year; in some years in the 1990's the eastern United States is cooler than climatology (the control run mean).

Conclusion. It is not possible to blame a specific heatwave/drought on the greenhouse effect. However, there is evidence that the greenhouse effect increases the likelihood of such events; our climate model simulations for the late 1980's and the 1990's indicate a tendency for an increase of heatwave/drought situations in the Southeast and Midwest United States. We note that the correlations between climate models and observed temperatures are often very poor at subcontinental scales, particularly during Northern Hemisphere summer (reference 7). Thus improved understanding of these phenomena depends upon the

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development of increasingly realistic global climate models and upon the availability of global observations needed to verify and improve the models.

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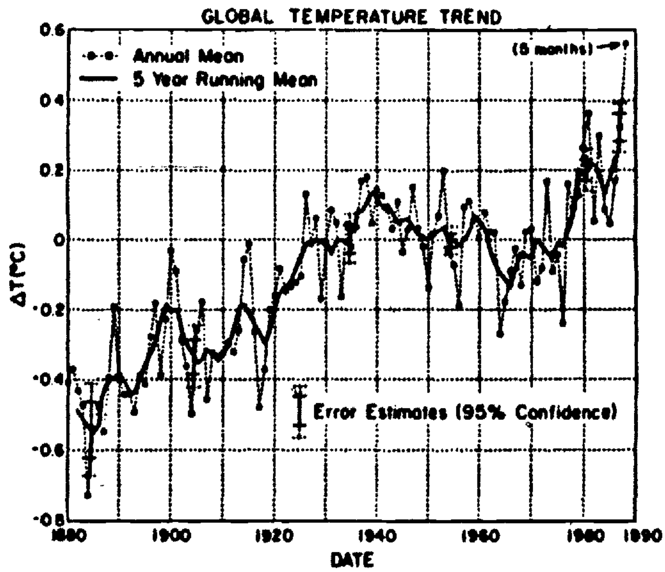

Fig. 1. Global surface air temperature change for the past century, with the zero point defined as the 1951-1980 mean. Uncertainty bars (95% confidence limits) are based on an error analysis as described in reference 6; inner bars refer to the 5-year mean and outer bars to the annual mean. The analyzed uncertainty is a result of incomplete spatial coverage by measurement stations, primarily in ocean areas. The 1988 point compares the January-May 1988 temperature to the mean for the same 5 months in 1951-1980.

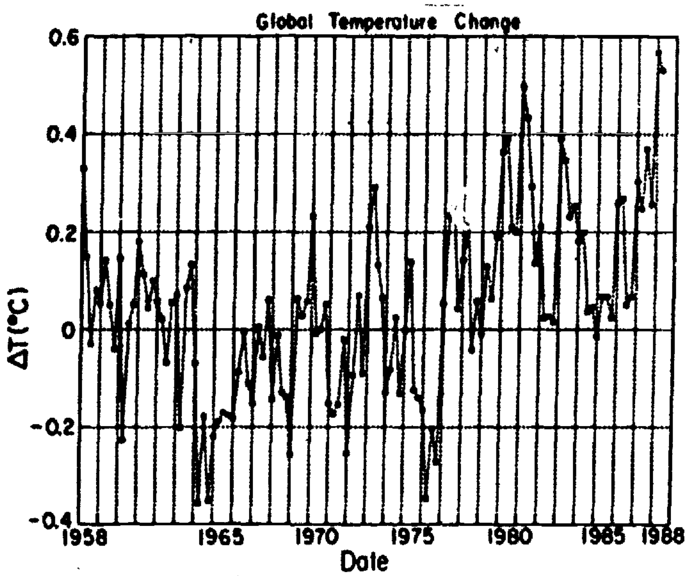

Fig. 2. Global surface air temperature change at seasonal resolution for the past 30 years. Figures 1 and 2 are updates of results in reference 6.

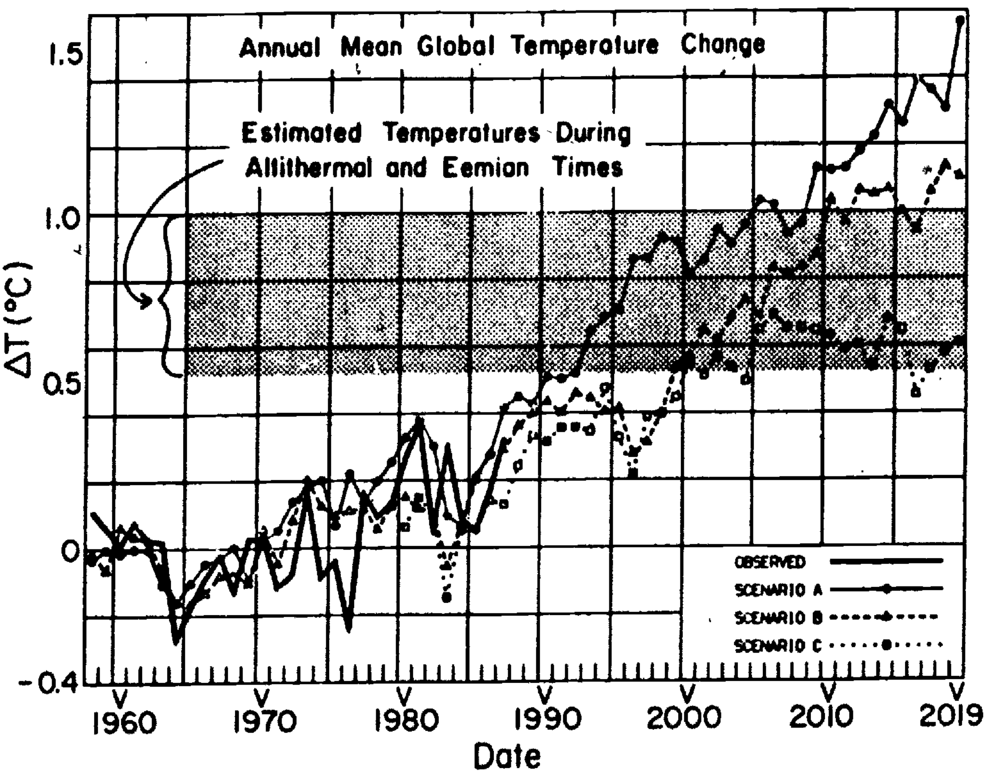

Fig. 3. Annual mean global surface air temperature computed for trace gas scenarios A, B and C described in reference 1. [Scenario A assumes continued growth rates of trace gas emissions typical of the past 20 years, i.e., about 1.5% yr^{-1} emission growth; scenario B has emission rates approximately fixed at current rates; scenario C drastically reduces trace gas emissions between 1990 and 2000.] Observed temperatures are from reference 6. The shaded range is an estimate of global temperature during the peak of the current and previous interglacial periods, about 6,000 and 120,000 years before present, respectively. The zero point for observations is the 1951-1980 mean (reference 6); the zero point for the model is the control run mean.

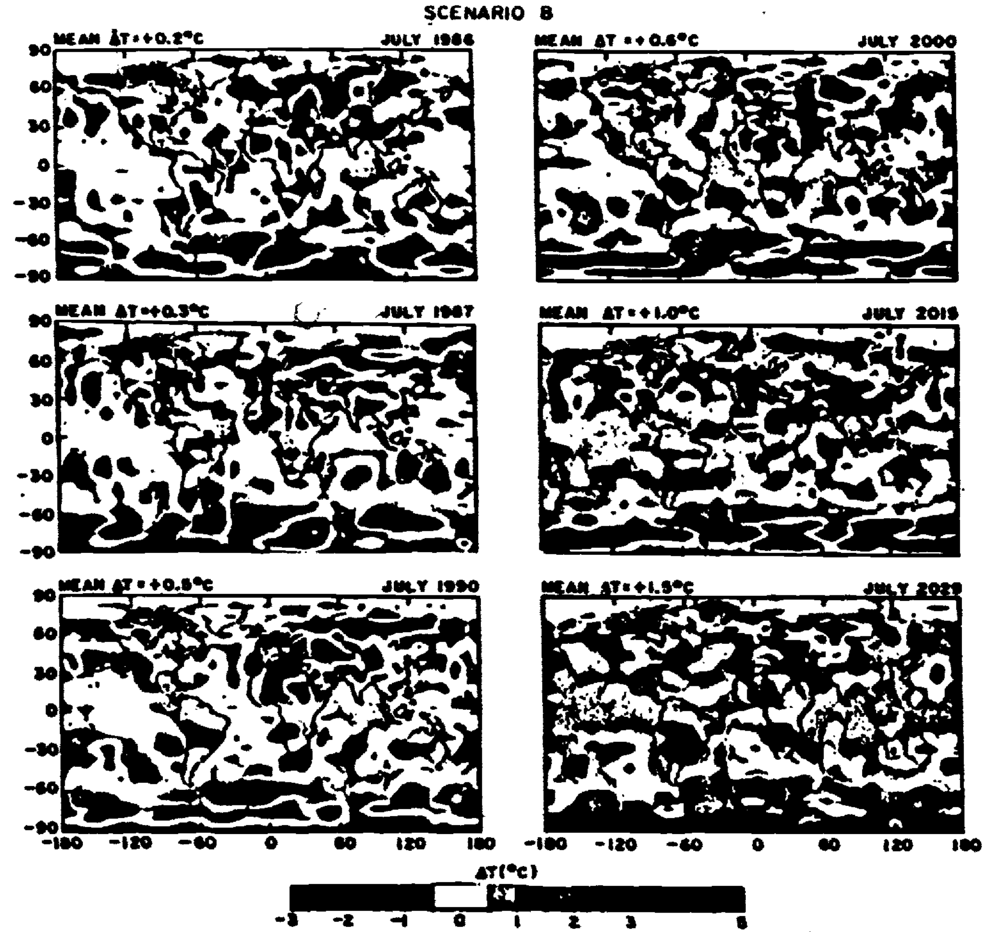

Fig. 4. Simulated July surface air temperature anomalies for six individual years of scenario B, compared to a 100 year control run with 1958 atmospheric composition (see Attachment A).

ATTACHMENT A

Global Climate Changes as Forecast by the GISS 3-D Model

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We use a three-dimensional climate model, our Model II with 8° by 10° horizontal resolution, to simulate the global climate effects of time dependent variations of atmospheric trace gases and aerosols. Horizontal heat transport by the ocean is fixed at values estimated for today's climate and uptake of heat perturbations by the ocean beneath the mixed layer is approximated as vertical diffusion. We make a 100 year control run and perform experiments for three scenarios of atmospheric composition. These experiments begin in 1958 and include measured or estimated changes in atmospheric CO_2, CH_4, N_2O, CFCs and stratospheric aerosols for the period from 1958 to the present. Scenario A assumes continued exponential trace gas growth, scenario B assumes a reduced linear growth of trace gases, and scenario C assumes a rapid curtailment of trace gas emissions such that the net climate forcing ceases to increase after 2000. Principal results from the experiments are: (1) Global warming to the level attained at the peak of the current interglacial and the previous interglacial occurs in all three scenarios; however, there are dramatic differences in the levels of future warming, depending on trace gas growth. (2) The greenhouse warming should be clearly identifiable in the 1990s; the global warming within the next several years is predicted to reach and maintain a level at least three standard deviations above the climatology of the 1950s. (3) Regions where an unambiguous warming appears earliest are low latitude oceans, China and interior areas in Asia, and ocean areas near Antarctica and the North Pole; aspects of the spatial and temporal distribution of predicted warming are clearly model-dependent, implying the possibility of model discrimination by the 1990s and thus improved predictions, if appropriate observations are acquired. (4) The temperature changes are sufficiently large to have major impacts on people and other parts of the biosphere, as shown by computed changes in the frequency of extreme events and by comparison with previous climate trends. (5) The model results suggest some near-term regional climate variations, despite the fixed ocean heat transport which suppresses many possible regional climate fluctuations; for example, during the late 1980s and in the 1990s there is a tendency for greater than average warming in the Southeast and Central U.S. and relatively cooler conditions or less than average warming in the western U.S. and much of Europe. Principal uncertainties in the predictions involve the equilibrium sensitivity of the model to climate forcing, the assumptions regarding heat uptake and transport by the ocean, and the omission of other less certain climate forcings.

to appear in <u>J. Geophys. Res.</u>

1. Introduction

Studies of the climate impact of increasing atmospheric CO_2 have been made by means of experiments with three-dimensional (3-D) climate models in which the amount of CO_2 was instantaneously doubled or quadrupled, with the model then integrated forward in time to a new steady state [*Manabe and Wetherald*, 1975; *Manabe and Stouffer*, 1980; *Hansen et al.*, 1984; *Washington and Meehl*, 1984; *Wilson and Mitchell*, 1987]. These models all yield a large climate impact at equilibrium for doubled CO_2, with global mean warming of surface air between about 2°C and 5°C.

However, observations show that CO_2 is increasing gradually: its abundance was 315 ppm (parts per million by volume) in 1958 when Keeling initiated accurate measurements and is now about 345 ppm, with current mean annual increments of about 1.5 ppm [*Keeling et al.*, 1982]. Also there are at least two other known global radiative forcings of comparable magnitude: growth of several other trace gases [*Wang et al.*, 1976; *Lacis et al.*, 1981; *Ramanathan et al.*, 1985] and variations in stratospheric aerosols due to volcanic eruptions [*Lamb*, 1970; *Mitchell*, 1970; *Schneider and Mass*, 1975; *Pollack et al.*, 1976, *Hansen et al.*, 1978, 1980; Robock, 1981]. Still other radiative forcings, such as changes of solar irradiance, tropospheric aerosols and land surface properties may also be significant, but quantitative information is insufficient to define the trends of these forcings over the past several decades.

In this paper we study the response of a 3-D global climate model to realistic rates of change of radiative forcing mechanisms. The transient response of the climate system on decadal time scales depends crucially on the response of the ocean, for which adequate understanding and dynamical models are not available. Our procedure is to use simple assumptions about ocean heat transport, specifically we assume that during the next few decades the rate and pattern of horizontal ocean heat transport will remain unchanged and the rate of heat uptake by the ocean beneath the mixed layer can be approximated by diffusive mixing of heat perturbations. This "surprise-free" representation of the ocean provides a first estimate of the global transient climate response which can be compared to both observations and future simulations developed with a dynamically interactive ocean. We include in this paper a description of the experiments and an analysis of computed temperature changes; other computed quantities, such as changes in the atmospheric general circulation, precipitation and sea ice cover will be presented elsewhere.

The climate model employed in our studies is described in Section 2. Results of a 100 year control run of this model, with the atmospheric composition fixed, are briefly described in Section 3. Three scenarios for atmospheric trace gases and stratospheric aerosols are defined in Section 4. Results of the climate model simulations for these three scenarios are presented in Section 5; Section 5.1 examines the predicted global warming and the issue of when the global warming should exceed natural climate variability, Section 5.2 examines the spatial distribution of predicted decadal temperature changes, and Section 5.3 examines short-term and local temperature changes. In the final section, we summarize the model predictions and discuss the principal caveats and assumptions upon which the results depend.

Our transient climate experiments were initiated in early 1983, being run as a background job on the GISS mainframe computer, a general purpose machine (Amdahl V-6) of mid-1970s vintage. Results for scenario A were reported at a conference in June 1984 (proceedings published by *Shands and Hoffman*, [1987]) and results from all scenarios were presented at several later conferences.

2. Climate Model

The atmospheric component of the global climate model we employ is described and its abilities and limitations for simulating today's climate are documented as model II [*Hansen et al.*, 1983, hereafter referred to as paper 1]. The model solves the simultaneous equations for conservation of energy, momentum, mass and water vapor and the equation of state on a coarse grid with nine atmospheric layers and horizontal resolution 8° latitude by 10° longitude. The radiation calculation includes the radiatively significant atmospheric gases, aerosols and cloud particles. Cloud cover and height are computed, but cloud opacity is specified as a function of cloud type, altitude and thickness. The diurnal and seasonal cycles are included. The ground hydrology and surface albedo depend upon the local vegetation. Snow depth is computed and snow albedo includes effects of snow age and masking by vegetation. The equilibrium sensitivity of this model for doubled CO_2 (315 ppm → 630 ppm) is 4.2°C for global mean surface air temperature [*Hansen et al.*, 1984, hereafter referred to as paper 2]. This is within, but near the upper end of, the range 3 ± 1.5°C estimated for climate sensitivity by National Academy of Sciences committees [*Charney*, 1979; *Smagorinsky*, 1982], where their range is a subjective estimate of the uncertainty based on climate modeling studies and empirical evidence for climate sensitivity. The sensitivity of our model is near the middle of the range obtained in recent studies with GCMs [*Washington and Meehl*, 1984; *paper 2*, 1984; *Manabe and Wetherald*, 1987; *Wilson and Mitchell*, 1987].

Ocean temperature and ice cover were specified climatologically in the version of model II documented in paper 1. In the experiments described here and in paper 2, ocean temperature and ice cover are computed based on energy exchange with the atmosphere, ocean heat transport, and the ocean's heat capacity. The treatments of ocean temperature and ice cover are nearly the same here as in paper 2, with the following exception. In paper 2, since the objective was to study equilibrium ($t \to \infty$) climate changes, computer time was saved by specifying the maximum mixed layer depth as 65m and by allowing no exchange of heat between the mixed layer and the deeper ocean. In this paper, since we are concerned with the transient climate response, we include the entire mixed layer with seasonally varying depth specified from observations as described in Appendix A and (except in the control run) we allow diffusive vertical heat transport beneath the level defined by the annual-maximum mixed layer depth. The global mean depth of this level is about 125 m and the effective global diffusion coefficient beneath it is about 1 cm^2s^{-1}.

The horizontal transport of heat in the ocean is specified from estimates for today's ocean, varying seasonally at each gridpoint, as described in Appendix A. In our experiments with changing atmospheric composition we keep the ocean horizontal heat transport (and the mixed layer depth) identical to that in the control run, i.e., no feedback of climate change on ocean heat transport is permitted in these experiments. Our rationale for this approach as a first step is that it permits a realistic atmospheric simulation and simplifies analysis of the experiments. Initial experiments with an idealized interactive atmosphere/ocean model suggest that the assumption of no feedback may be a good first approximation for small climate perturbations in the direction of a warmer climate [*Bryan et al.*, 1984; *Manabe and Bryan*, 1985]. In addition, experiments with a zonal average heat balance model suggest that the global average climate sensitivity does not depend strongly on the feedback in the ocean heat transport [*Wang et al.*, 1984]. However, we stress that this "surprise-free" representation of the ocean excludes the effects of natural variability of ocean transports and the possibility of switches in the basic mode of ocean circulation. *Broecker et al.* [1985], for example, have suggested that sudden changes in the rate of deep water formation may be associated with oscillations of the climate system. Discussions of the transient ocean response have been given by Schneider and Thompson [1981], Bryan et al. [1984], and others. We consider our simple treatment of the ocean to be only a first step in studying the climate response to a slowly changing climate forcing, one which must be compared with results from dynamically interactive ocean models when such models are applied to this problem.

3. 100 Year Control Run

A 100 year control run of the model was carried out with the atmospheric composition fixed at estimated 1958 values. Specifically, atmospheric gases which are time dependent in later experiments are set at the values 315 ppm for CO_2, 1400 ppb for CH_4, 292.6 ppb for N_2O, 15.8 ppt for CCl_3F (F11), and 50.3 ppt for CCl_2F_2 (F12).

The ocean mixed layer depth varies geographically and seasonally based on climatological data specified in Appendix A. No heat exchange across the level defined by the annual maximum mixed layer depth was permitted in the control run described in this section. The purpose of this constraint was to keep the response time of the model short enough that it was practical to extend the model integration over several time constants, thus assuring near equilibrium conditions. The isolated mixed layer response time is 10-20 years for a climate sensitivity of 4°C for doubled CO_2, as shown in paper 2. Note that the seasonal thermocline (i.e., the water between the base of the seasonal mixed layer and the annual-maximum mixed layer depth) can have a different temperature each year; this heat storage and release can affect the interannual variability of surface temperature.

The variation of the global-mean annual-mean surface air temperature during the 100 year control run is shown in Figure 1. The global mean temperature at the end of the run is very similar to that at the beginning, but there is substantial unforced variability on all time scales that can be examined, that is, up to decadal time scales. Note that an unforced change in global temperature of about 0.4°C (0.3°C if the curve is smoothed with a 5 year running mean) occurred in one 20 year period (years 50-70). The standard deviation about the 100 year mean is 0.11°C. This unforced variability of global temperature in the model is only slightly smaller than the observed variability of global surface air temperature in the past century, as discussed in Section 5. The conclusion that unforced (and unpredictable) climate variability may account for a large portion of past climate change has been stressed by many researchers; for example, Lorenz [1968], Hasselman [1976] and Robock [1978].

The spatial distribution of the interannual variability of temperature in the model is compared with observational data in Plate 1. The geographical distribution of surface air temperature variability is shown in Plate 1*a* for the model and Plate 1*b* for observations. The standard deviation ranges from about 0.25°C at low latitudes to more than 1°C at high latitudes, in both the model and observations. The model's variability tends to be larger than observed over continents; this arises mainly from unrealistically large model variability (by about a factor of two) over the continents in summer, as shown by the seasonal graphs of *Hansen and Lebedeff* [1987]. The interannual variability of the zonal mean surface air temperature, as a function of latitude and month, is shown in Plate 1*c* and 1*d* for the model and observations. The seasonal distribution of variability in the model is generally realistic, except that the summer minimum in the Northern Hemisphere occurs about one month early. The interannual variability of temperature as a function of height is more difficult to check, because observations of sufficient accuracy are limited to radiosonde data. J. Angell (private communication) has analyzed data from 63 radiosonde stations, averaged the temperature change zonally, and tabulated the data with a resolution of seven latitude bands and four heights, the lowest of these heights being the surface air; the interannual variability of the results is shown in Plate 1*f*. Reasons for smaller variability in the model, Plate 1*e*, probably include: (1) identical ocean heat transport every year, which inhibits occurrence of phenomena such as El Niño and the associated variability of upper air temperature, and (2) stratospheric drag in the upper model layer of the 9-layer model II, which reduces variability in the stratosphere and upper troposphere as shown by experiments with a 23-layer version of the model which has its top at 85 km [*Rind et al.*, 1988].

We use these interannual variabilities in Section 5 to help estimate the significance of predicted climate trends and to study where it should be most profitable to search for early evidence of greenhouse climate effects. We defer further discussion of model variability and observed variability to that section.

4. Radiative Forcing in Scenarios A, B and C

4.1. *Trace gases*

We define three trace gas scenarios to provide an indication of how the predicted climate trend depends upon trace gas growth rates. Scenario A assumes that growth rates of trace gas emissions typical of the 1970s and 1980s will continue indefinitely; the assumed annual growth averages about 1.5% of current emissions, so the net greenhouse forcing increases exponentially. Scenario B has decreasing trace gas growth rates such that the annual increase of the greenhouse climate forcing remains approximately constant at the present level. Scenario C drastically reduces trace gas growth between 1990 and 2000 such that the greenhouse climate forcing ceases to increase after 2000. The range of climate forcings covered by the three scenarios is further increased by the fact that scenario A includes the effect of several hypothetical or crudely estimated trace gas trends (ozone, stratospheric water vapor, and minor chlorine and fluorine compounds) which are not included in scenarios B and C.

These scenarios are designed to yield sensitivity experiments for a broad range of future greenhouse forcings. Scenario A, since it is exponential, must eventually be on the high side of reality in view of finite resource constraints and environmental concerns, even though the growth of emissions in Scenario A ($\approx$ 1.5% yr^{-1}) is less than the rate typical of the past century ($\approx$ 4% yr^{-1}). Scenario C is a more drastic curtailment of emissions than has generally been imagined; it represents elimination of chlorofluorocarbon emissions by 2000 and reduction of CO_2 and other trace gas emissions to a level such that the annual growth rates are zero (i.e., the sources just balance the sinks) by the year 2000. Scenario B is perhaps the most plausible of the three cases.

The abundances of the trace gases in these three scenarios are specified in detail in Appendix B. The net greenhouse forcing, ΔT_0, for these scenarios is illustrated in Figure 2; ΔT_0 is the computed temperature change at equilibrium ($t \to \infty$) for the given change in trace gas abundances, with no climate feedbacks included [*paper* 2]. Scenario A reaches a climate forcing equivalent to doubled CO_2 in about 2030, scenario B reaches that level in about 2060, and scenario C never approaches that level. Note that our scenario A goes approximately through the middle of the range of likely climate forcing estimated for 2030 by *Ramanathan et al.* [1985], and scenario B is near the lower limit of their estimated range. Note also that the forcing in scenario A exceeds that for scenarios B and C for the period from 1958 to the present, even though the forcing in that period is nominally based on observations; this is because scenario A includes a forcing for some speculative trace gas changes in addition to the measured ones (cf. Appendix B).

Our climate model computes explicitly the radiative forcing due to each of the above trace gases, using the correlated k-distribution method [*paper* 1]. However, we anticipate that the climate response to a given global radiative forcing ΔT_0 is similar to first order for different gases, as supported by calculations for different climate forcings in paper 2. Therefore, results obtained for our three scenarios provide an indication of the expected climate response for a very broad range of assumptions about trace gas trends. The forcing for any other scenario of atmospheric trace gases can be compared to these three cases by computing $\Delta T_0(t)$ with formulas provided in Appendix B.

4.2. *Stratospheric aerosols*

Stratospheric aerosols provide a second variable climate forcing in our experiments. This forcing is identical in all three experiments for the period 1958–1985, during which time there were two substantial volcanic eruptions, Agung in 1963 and El Chichón in 1982. In scenarios B and C, additional large volcanoes are inserted in 1995 (identical in properties to El Chichón), in 2015 (identical to Agung), and in 2025 (identical to El Chichón), while in scenario A no additional volcanic aerosols are included after those from El Chichón have decayed to the background stratospheric aerosol level. The stratospheric aerosols in scenario A are thus an extreme case, amounting to an assumption that the next few decades will be similar to the few decades before 1963, which were free of any volcanic eruptions creating large stratospheric optical depths. Scenarios B and C in effect use the assumption that the mean stratospheric aerosol optical depth during the next few decades will be comparable to that in the volcanically active period 1958–1985.

The radiative forcing due to stratospheric aerosols depends upon their physical properties and global distribution. Sufficient observational data on stratospheric opacities and aerosol properties is available to define the stratospheric aerosol forcing reasonably well during the past few decades, as described in Appendix B. We subjectively estimate the uncertainty in the global mean forcing due to stratospheric aerosols as about 25% for the period from 1958 to the present. It should be possible eventually to improve the estimated aerosol forcing for the 1980s, as discussed in Appendix B.

The global radiative forcing due to aerosols and greenhouse gases is shown in the lower panel of Figure 2. Stratospheric aerosols have a substantial effect on the net forcing for a few years after major eruptions, but within a few decades the cumulative CO_2/trace gas warming in scenarios A and B is much greater than the aerosol cooling.

5. Transient Simulations

5.1. *Global Mean Surface Air Temperature*

The global mean surface air temperature computed for scenarios A, B and C is shown in Figure 3 and compared with observations, the latter based on analyses of *Hansen and Lebedeff* [1987] updated to include 1986 and 1987 data. Figure 3*a* is the annual mean result and Figure 3*b* is the five year running mean. In Figure 3*a* the temperature range 0.5°-1.0°C above 1951-1980 climatology is noted as an estimate of peak global temperatures in the current and previous interglacial periods, based on several climate indicators [*NAS*, 1975]; despite uncertainties in reconstructing global temperatures at those times, it is significant that recent interglacial periods were not much warmer than today.

Interpretation of Figure 3 requires quantification of the magnitude of natural variability, in both the model and observations, and the uncertainty in the measurements. As mentioned in the description of Figure 1, the standard deviation of the model's global mean temperature is 0.11°C for the 100 year control run, which does not include the thermocline. The model simulations for scenarios A, B and C include the thermocline heat capacity which slightly reduces the model's short-term variability; however, judging from the results for scenario A, which has a smooth variation of climate forcing, the models's standard deviation remains about 0.1°C. The standard deviation about the 100 year mean for the observed surface air temperature change of the past century (which has a strong trend) is 0.20°C; it is 0.12°C after detrending [*Hansen et al.*, 1981]. The 0.12°C detrended variability of observed temperatures was obtained as the average standard deviation about the ten 10-year means in the past century; if, instead, we compute the average standard deviation about the four 25-year means, this detrended variability is 0.13°C. For the period 1951-1980, which is commonly used as a reference period, the standard deviation of annual temperature about the 30-year mean is 0.13°C. It is not surprising that the variability of the observed global temperature exceeds the variability in the GCM control run, since the latter contains no variable climate forcings such as changes of atmospheric composition or solar irradiance; also specification of ocean heat transport reduces interannual variability due to such phenomena as El Niño/Southern Oscillation events. Finally, we note that the one-sigma error in the observations due to incomplete coverage of stations is about 0.05°C for the period from 1958 to the present [*Hansen and Lebedeff*, 1987], which does not contribute appreciably to the variability (standard deviation) of the observed global temperature. We conclude that, on a time scale of a few decades or less, a warming of about 0.4°C is required to be significant at the 3σ level (99% confidence level).

There is no obviously significant warming trend in either the model or observations for the period 1958-1985. During the single year 1981 the observed temperature nearly reached the 0.4°C level of warming, but in 1984 and 1985 the observed temperature was no greater than in 1958. Early reports show that the observed temperature in 1987 again approached the 0.4°C level [*Hansen and Lebedeff*, 1988], principally as a result of high tropical temperatures associated with an El Niño event which was present for the full year. Analyses of the influence of previous El Niños on Northern Hemisphere upper air temperatures [*Peixoto and Oort*, 1984] suggest that global temperature may decrease in the next year or two.

The model predicts, however, that within the next several years the global temperature will reach and maintain a 3σ level of global warming, which is obviously significant. Although this conclusion depends upon certain assumptions, such as the climate sensitivity of the model and the absence of large volcanic eruptions in the next few years, as discussed below in Section 6, it is robust for a very broad range of assumptions about CO_2 and trace gas trends, as illustrated in Figure 3.

Another conclusion is that global warming to the level attained at the peak of the current interglacial and the previous interglacial appears to be inevitable; even with the drastic, and probably unrealistic, reductions of greenhouse forcings in scenario C, a warming of 0.5°C is attained within the next 15 years. The eventual warming in this scenario would exceed 1°C, based on the forcing illustrated in Figure 2 and the feedback factor $f = 3.4$ for our GCM [*paper 2*]. The 1°C level of warming is exceeded during the next few decades in both scenarios A and B; in scenario A that level of warming is reached in less than 20 years and in scenario B it is reached within the next 25 years.

5.2. *Spatial Distribution of Decadal Temperature Changes*

5.2.1. *Geographical distribution*. The geographical distribution of the predicted surface air temperature change for the intermediate scenario B is illustrated in the left column of Plate 2 for the 1980s, 1990s and 2010s. The right column is the ratio of this decadal temperature change to the interannual variability (standard deviation) of the local temperature in the 100 year control run (Plate 1*a*). Since the interannual variability of surface air temperature in the model is reasonably similar to the variability in the real world (Plate 1*b*), this ratio provides a practical measure of when the predicted mean greenhouse warming is locally significant.

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

The warming is generally greater over land than over the ocean, and greater at high latitudes than at low latitudes, being especially large in regions of sea ice. Regions where the warming shows up most prominently in our model, relative to the interannual variability, are: (1) low latitude ocean regions where the surface response time is small (Figure 15 of paper 2) due to a shallow ocean mixed layer and small thermocline diffusion, specifically regions such as the Caribbean, East Indies, Bay of Bengal, and large parts of the Indian, Atlantic and Pacific Oceans near or just north of the equator, (2) China, where the model's variability is twice as large as the observed variability, (cf. Plate 1) and the interior downwind portion of the Eurasian continent, especially the Kazakh-Tibet-Mongolia-Manchuria region, and (3) ocean areas near Antarctica and the North Pole, where sea ice provides a positive climate feedback. The regions predicted to have earliest detectability of greenhouse warming are undoubtedly model dependent to some extent; as discussed below, this model dependence, in conjunction with global observations, may soon provide valuable information on climate mechanisms.

The predicted signal/noise ratio ($\Delta T/\sigma$) is generally smaller at any given geographical location than it is for the global mean (Figure 3), because the noise is significantly reduced in the global average. Thus for the single purpose of detecting a greenhouse warming trend, the global mean temperature provides the best signal. The geographical distribution of the predicted global temperature change also can be used for "optimal weighting" of global data to enhance early detection of a climate trend [*Bell*, 1982], but the impact of such weighting is modest and model dependent.

Our results suggest that the geographical patterns of model predicted temperature change, in combination with observations, should become valuable soon for discriminating among alternative model results, thus providing information on key climate processes which in turn may help narrow the range for predictions of future climate. For example, Plate 2 shows a strong warming trend in sea ice regions bordering the Antarctic continent; on the contrary, the ocean atmosphere model of *Manabe and Bryan* (private communication) shows cooling in this region for the first few decades after an instant doubling of atmospheric CO_2. The contrary results probably arise from different heat transports by the oceans in the GISS and GFDL models. As a second example, our model yields a strong warming trend at low latitudes as does the BMO model [*Wilson and Mitchell*, 1987], while the GFDL and NCAR models [*Washington and Meehl*, 1984] yield minimal warming at low latitudes. The contrary results in this case may arise from the treatments of moist convection, as the GISS and BMO models use penetrative convection schemes and the GFDL and NCAR models use a moist adiabatic adjustment. Judging from Plate 2, the real world laboratory may provide empirical evidence relating to such climate mechanisms by the 1990s.

5.2.2. *Latitude-season distribution*. The dependence of the predicted temperature changes on season is investigated in Plate 3, which shows the predicted surface air temperature change for scenario B as a function of latitude and month (left side) and the ratio of this to the model's interannual variability (right side). Although the largest ΔT's are at high latitudes and in the winter, the variability is also largest at high latitudes and in the winter. Considering also the differences between the model's variability and observed variability (Plate 1), Plate 3 suggests that the best place to look for greenhouse warming in the surface air may be middle and low latitudes in both hemispheres, with signal/noise in summer being as great or greater than in winter.

5.2.3. *Latitude-height distribution*. The dependence of the predicted temperature changes on altitude is investigated in Plate 4, which shows the predicted upper air temperature change as a function of pressure and latitude (left side) and the ratio of this to the model's interannual variability (right side). Although the predicted greenhouse warming in our climate model is greater in the upper troposphere at low latitudes than it is at the surface, the signal/noise ratio does not have a strong height dependence in the troposphere. The dominant characteristic of the predicted atmospheric temperature change is stratospheric cooling with tropospheric warming. This characteristic could be a useful diagnostic for the greenhouse effect, since, for example, a tropospheric warming due to increased solar irradiance should be accompanied by only a slight stratospheric cooling (cf. Figure 4 in paper 2). However, the large signal/noise for the stratospheric cooling in Plate 4 is partly an artifact of the unrealistically small variability at stratospheric levels in our 9-layer model; the model predictions there need to be studied further with a model which has more appropriate vertical structure.

5.2.4. *Comparisons with observations*. Global maps of observed surface air temperature for the first seven years of the 1980's show measurable warming, compared to observations for 1951-1980, especially in central Asia, northern North America, the tropics, and near some sea ice regions [*Hansen et al.*, 1987]. There are general similarities between these observed patterns of warming and the model results (Plate 2); the magnitude of the warming is typically in the range 0.5-1.0σ defined in Plate 1. Perhaps a more quantitative statement could be made by using the observational and model data in detection schemes which optimally weight different geographical regions [e.g., *Bell*, 1982; *Barnett*, 1986]. The significance of such comparisons should increase after data are available for the last few years of the 1980s, which are particularly warm in the model. However, information from the pattern of surface warming is limited by the fact that similar patterns can result from different climate forcings [*Manabe and Wetherald*, 1975; *paper 2*].

Comparisons of temperature changes as a function of height may be more diagnostic of the greenhouse effect, as mentioned above. Analysis of radiosonde data for the period 1960-1985 by *Angell* [1986] suggests a global warming of about 0.3°C in the 300-850 mb region and a cooling of about 0.5°C in the 100-300 mb and 50-100 mb regions over that 25 year period. Although the warming in the lower troposphere and cooling in the stratosphere are consistent with our model results (Plate 4), the upper tropospheric (100-300 mb) cooling is not. The temperature changes are about 0.5-1σ, based on the natural variability in the model and observations (Plate 1). Note that our illustrated model results are for the period 1980-1989.

None of the climate models which have been applied to the greenhouse climate problem yield upper tropospheric cooling as found in observations by *Angell* [1986]. If this characteristic of the observations persists over the next several years, as the modeled temperature changes reach higher levels of mathematical significance, it will suggest either a common problem in the models or that we need to include additional climate forcing mechanisms in the analyses. Although the trend in the observations is not yet clear, it is perhaps worthwhile to point out examples of mechanisms which could produce a discrepancy between model and observations.

Concerning possible common model problems, a prime a priori candidate would be the modeling of moist convection, since it is a principal process determining the vertical temperature gradient. However, the treatment of convection in the models (GFDL, GISS, NCAR and BMO) ranges from moist adiabatic adjustment to penetrating convection, and all of these models obtain strong upper tropospheric warming. A more likely candidate among internal model deficiencies may be the cloud feedback. Although some of the models include dynamical/radiative cloud feedback, they do not include optical/radiative feedbacks. For example, it is possible that the opacity of (upper tropospheric) cirrus clouds may increase in a warming climate; this would increase the greenhouse effect at the surface while causing a cooling in the upper troposphere.

A good candidate for changing the temperature profile among climate forcings is change of the vertical profile of ozone, since some observations suggest decreasing ozone amounts in the upper troposphere and stratosphere along with increases in the lower troposphere [*Bolle et al.*, 1986]. Another candidate climate forcing is change of the atmospheric aerosol distribution; as discussed in Appendix B, it will be possible to specify changes of stratospheric aerosols in the 1980s more accurately than we have attempted in this paper, but little information is available on changes in tropospheric aerosols. Still another candidate climate forcing is solar variability; although changes of total solar irradiance such as reported by *Wilson et al.* [1986] would not yield opposite responses in the upper and lower troposphere, changes in the spectral distribution of the solar irradiance may have a more complicated effect on temperature profiles.

These examples point out the need for several observations of climate forcing mechanisms and climate feedback processes during coming years as the greenhouse effect increases. Such observations are essential if we are to reliably interpret the causes of climate change and the implications for further change.

5.3. *Short-term and Local Temperature Changes*

Although long-term large-area averages increase the signal/noise ratio of greenhouse effects, it is important to also examine the model predictions for evidence of greenhouse effects on the frequency and global distribution of short-term climate disturbances. Such studies will be needed to help answer practical questions, such as whether the greenhouse effect has a role in observed local and regional climate fluctuations.

We illustrate here samples of model results at seasonal and monthly temporal resolutions, and we estimate the effect of the temperature changes on the frequency of extreme temperatures at specific locales. The object is not to make predictions for specific years and locations, but rather to provide some indication of the magnitude of practical impacts of the predicted temperature changes.

5.3.1. *Summer and winter maps*. We compare in Plate 5 the computed temperature changes in scenarios A, B and C for June-July-August and December-January-February of the 1990s. In both seasons the warming is much greater in scenario A than in scenarios B and C, as also illustrated in Figure 3. The relative warmings are consistent with the global radiative forcings for the three scenarios shown in Figure 2; the greater forcing in scenario A arises partly from greater trace gas abundances and partly from the assumed absence of large volcanic eruptions.

Features in the predicted warming common to all scenarios include a tendency for the greatest warming to be in sea ice regions and land areas, as opposed to the open oceans. At high latitudes the warming is greater in winter than in summer. We also notice a tendency for certain patterns in the warming, for example, greater than average warming in the eastern United States and less warming in the western United States. Examination of the changes in sea level pressure and atmospheric winds suggests that this pattern in the model may be related to the ocean's response time: the relatively slow warming of surface waters in the mid Atlantic off the Eastern United States and in the Pacific off California tends to increase sea level pressure in those ocean regions and this in turn tends to cause more southerly winds in the eastern United States and more northerly winds in the western United States. However, the tendency is too small to be apparent every year; in some years in the 1990s the eastern United States is cooler than climatology (the control run mean) and often the western United States is substantially warmer than climatology. Moreover, these regional patterns in the warming could be modified if there were major changes in ocean heat transports.

5.3.2. *July maps*. We examine in Plate 6 the temperature changes in a single month (July) for several different years of scenario B. In the 1980s the global warming is small compared to the natural variability of local monthly mean temperature; thus any given location is about as likely to be cooler than climatology as warmer than climatology, and, as shown in Plate 6, the area with cool temperatures in a given July is about as great as the area with warm temperatures. But by the year 2000 there is an obvious tendency for it to be warm in more regions, and by 2029 it is warm almost everywhere.

Monthly temperature anomalies can be readily noticed by the average person or "man-in-the-street". A calibration of the magnitude of the model predicted warming can be obtained by comparison of Plate 6 with maps of observations for recent years, as published by *Hansen et al.* [1987] using the same color scale as employed here. This comparison shows that the warm events predicted to occur by the 2010s and 2020s are much more severe than those of recent experience, such as the July 1986 heat wave in the Southeast United States, judging from the area and magnitude of the hot regions.

5.3.3. *Frequency of extreme events.* Although the greenhouse effect is usually measured by the change of mean temperature, the frequency and severity of extreme temperature events is probably of greater importance to the biosphere. Both plants and animals are affected by extreme temperatures, and regions of habitability are thus often defined by the range of local temperatures.

We estimate the effect of greenhouse warming on the frequency of extreme temperatures by adding the model predicted warming for a given decade to observed local daily temperatures for the period 1950-1979. This procedure is intended to minimize the effect of errors in the control run climatology, which are typically several degrees Centigrade. The principal assumption in this procedure is that the shape of the temperature distribution about the mean will not change much as the greenhouse warming shifts the mean to higher values. We tested this assumption, as shown in Figure 4 for the 10 gridboxes which approximately cover the United States, and found it to be good. The illustrated case is the most extreme in our scenarios, the decade 2050s of scenario A, for which the global mean warming is about 4°C. Note in particular that there is no evidence that the distribution toward high temperatures in the summer becomes compressed toward the mean as the mean increases; indeed the small change in the distribution which occurs is in the sense of greater variability, suggesting that our assumption of no change in the distribution will yield a conservative estimate for the increase in the frequency of hot events.

We also examined the effect of the greenhouse warming on the amplitude of the diurnal cycle of surface air temperature. In our doubled CO_2 experiment [*paper 2*] the diurnal cycle over land areas decreased by 0.7°C, with greatest changes at low latitudes; for gridboxes in the United States the changes of diurnal amplitude ranged from a decrease of 0.8°C to an increase of 0.5°C. The changes of diurnal amplitude in the transient experiments varied from gridbox to gridbox, but did not exceed several tenths of a degree centigrade. Thus for simplicity we neglected this effect in our estimates of changes in the frequencies of extreme temperatures.

The estimated change in the mean number of days per year with temperature exceeding 95°F (35°C), minimum temperature exceeding 75°F (≈ 24°C), and minimum temperature below 32°F (0°C) is shown in Figure 5 for several cities. The scenario results were obtained by adding the mean decadal warming (relative to the last nine years of the control run) of the four model gridpoints nearest each city to the 1950-1979 observed temperatures. We employ a broad-area 10-year mean change, so that the variability is provided principally by the observed climatology.

The results in Figure 5 illustrate that the predicted changes in the frequency of extreme events in the 1990s generally are less than the observed interannual variability, but the changes become very large within the next few decades. The large effects are not a result of unusual local results in the model's computed ΔT. The computed warmings in the United States are typical of other land areas in the model. For the case of doubled CO_2, which we can compare with other models, the warming we obtain in the United States (about 4.5°C, see paper 2) is intermediate between the warmings in the GFDL (Manabe and Wetherald, 1987) and NCAR [*Washington and Meehl*, 1984] models.

Even small temperature changes, less than the interannual variability, can be noticeable to the "man-in-the-street" and have significant impacts on the biosphere. As one measure of the detectability of local greenhouse warming, we consider the frequency of warm summers. We arbitrarily define the 10 warmest summers (June-July-August) in the period 1950-1979 as "hot", the 10 coolest as "cold", and the middle 10 as "normal". The impact of the model-computed warming on the frequency of hot summers is illustrated in Figure 6 for the region of Washington D.C., based on the four gridboxes covering the eastern part of the United States, and for the region of Omaha, based on the four independent west-central gridboxes. In both regions by the 1990's the chance of a hot summer exceeds 50% in all three scenarios, and exceeds 70% in scenario A.

With hot, normal and cold summers defined by 1950-1979 observations as described above, the climatological probability of a hot summer could be represented by two faces (say painted red) of a six-faced die. Judging from our model, by the 1990s three or four of the six die faces will be red. It seems to us that this is a sufficient "loading" of the dice that it will be noticeable to the "man-in-the-street". We note, however, that, if say a blue die face is used for a cold summer, there is still one blue die face in both the 1990s and the first decade of the next century. Thus there remains a substantial likelihood of a cold season at any given location for many years into the future.

We concluded above that the magnitude of global mean greenhouse warming should be sufficiently large for scientific identification by the 1990s. We infer from the computed change in the frequency of warm summers that the "man-in-the-street" is likely to be ready to accept that scientific conclusion. We also conclude that, if the world follows a course between scenarios A and B, the temperature changes within several decades will become large enough to have major effects on the quality of life for mankind in many regions.

The computed temperature changes are sufficient to have a large impact on other parts of the biosphere. A warming of 0.5°C/decade implies typically a poleward shift of isotherms by 50 to 75 km per decade. This is an order of magnitude faster than the major climate shifts in the paleoclimate record, and faster than most plants and trees are thought to be capable of naturally migrating [Davis, 1988]. Managed crops will need to be adapted to more extreme conditions in many locales. For example, following the suggestion of S. Schneider (private communication), we estimated the effect of greenhouse warming on the likelihood of a run of five consecutive days with maximum temperature above 95°F. Observations at Omaha, Nebraska for the 30 year period 1950-1979 show 3 years/decade with at least one such run of 95°F temperatures. With the warming from our model this becomes 5 years/decade in the 1990s in scenario A (4 years/decade in scenarios B and C), 7 years/decade in the 2020s in scenario A (6 years/decade in scenario B and 4 years/decade in scenario C), and 9 years/decade for doubled CO_2. Such temperature extremes are thought to be harmful to corn productivity [*Mearns et al.*, 1984]; thus these results imply that the impact on crops can be very nonlinear with increasing mean temperature. Another example of nonlinear response by the biosphere to increasing temperature is evidence that many coral populations expell their symbiotic algae when water temperature rises above about 30°C, leading to death of the coral if temperatures remain in that range, as evidenced by recent events in the tropics [*Roberts*, 1987].

Negative impacts of greenhouse warming on the biosphere are undoubtedly greatest in regions where species are close to maximum-temperature tolerance limits. Such impacts may be at least partially balanced by improved opportunities for productive life in other regions. Also the "fertilization" effect on crops due to increasing atmospheric CO_2 [*Lemon*, 1983] and other greenhouse climate effects such as changes in precipitation [*Manabe and Wetherald*, 1987] may have impacts besides that of the temperature change. Our intention here is only to show that temperature changes themselves can have a major impact on life, and that these effects may begin to be felt soon. We emphasize that it is the possibility of rapid climate change which is of most concern for the biosphere; there may not be sufficient time for many biosystems to adapt to the rapid changes forecast for scenarios A and B.

6. Discussion

Our simulations of the global climate response to realistic time-dependent changes of atmospheric trace gases and aerosols yield the following results: (1) global warming within the next few decades at least to the maximum levels achieved during the last few interglacial periods occurs for all the trace gas scenarios which we consider, but the magnitude of further warming depends greatly on future trace gas growth rates; (2) the global greenhouse warming should rise above the level of natural climate variability within the next several years, and by the 1990s there should be a noticeable increase in the local frequency of warm events; (3) some regions where the warming should be apparent earliest are low latitude oceans, certain continental areas, and sea ice regions; the three-dimensional pattern of the predicted warming is model-dependent, implying that appropriate observations can provide discrimination among alternative model representations and thus lead to improved climate predictions; (4) the temperature changes are sufficiently large to have major impacts on man and his environment, as shown by computed changes in the frequency of extreme events and by comparison with previous climate trends; (5) some near-term regional climate variations are suggested; for example, there is a tendency in the model for greater than average warming in the Southeast and Central U.S. and relatively cooler conditions or less than average warming in the western U.S. and much of Europe in the late 1980s and in the 1990s.

In this section we summarize principal assumptions upon which these results depend. In the final subsection we stress the need for global observations and the development of more realistic models.

6.1. *Climate Sensitivity*

The climate model we employ has a global mean surface air equilibrium sensitivity of 4.2°C for doubled CO_2. Other recent GCM's yield equilibrium sensitivities of 2.5-5.5°C, and we have presented empirical evidence favoring the range 2.5-5°C [*paper* 2]. Reviews by the National Academy of Sciences [*Charney*, 1979; *Smagorinsky*, 1982] recommended the range 1.5-4.5°C, while a more recent review by *Dickinson* [1986] recommended 1.5-5.5°C.

Forecast temperature trends for time scales of a few decades or less are not very sensitive to the model's equilibrium climate sensitivity [*Hansen et al.*, 1985]. Therefore climate sensitivity would have to be much smaller than 4.2°C, say 1.5-2°C, in order to modify our conclusions significantly. Although we have argued [*paper* 2] that such a small sensitivity is unlikely, it would be useful for the sake of comparison to have GCM simulations analogous to the ones we presented here, but with a low climate sensitivity. Until such a study is completed, we can only state that the observed global temperature trend is consistent with the "high" climate sensitivity of the present model. However, extraction of the potential empirical information on climate sensitivity will require observations to reduce other uncertainties, as described below. The needed observations include other climate forcings and key climate processes such as the rate of heat storage in the ocean.

6.2. *Climate Forcings*

Climate forcing due to increasing atmospheric greenhouse gases in the period from 1958 to the present is uncertain by perhaps 20% (Appendix B); the uncertainty about future greenhouse forcing is considerably greater. Therefore our procedure has been to consider a broad range of trace gas scenarios and to provide formulae (Appendix B) which allow calculation of where the climate forcing of any alternative scenario fits within the range of forcings defined by our scenarios A, B and C.

We emphasize that as yet greenhouse gas climate forcing does not necessarily dominate over other global climate forcings. For example, measurements from the Nimbus 7 satellite show that the solar irradiance decreased by about 0.1% over the period 1979 to 1985 [*Wilson et al.*, 1986;

Frohlich, 1987]. As shown by formulae in Appendix B, this represents a negative climate forcing of the same order of magnitude as the positive forcing due to the increase of trace gases in the same period. The observed trend implies the existence of significant solar irradiance variations on decadal time scales, but does not provide information over a sufficient period for inclusion in our present simulations. The greenhouse gas forcing has increased more or less monotonically, at least since 1958; thus the greenhouse gas climate forcing in the 1980s including the "unrealized" warming [*Hansen et al.*, 1985] due to gases added to the atmosphere before the 1980s probably exceeds the solar irradiance forcing, unless there has been a consistent solar trend for two decades or more. If the solar irradiance continues to decrease at the rate of 1979–1985 it could reduce the warming predicted for the 1990s; on the other hand, if the decline of solar irradiance bottoms out in the late 1980's, as recent data suggest [*Hickey et al.*, 1987], and if the irradiance begins an extended upward trend, it is possible that the rate of warming in the next decade could exceed that in our present scenarios. Continued monitoring of the solar irradiance is essential for interpretation of near-term climate change and early identification of greenhouse warming.

Stratospheric aerosols also provide a significant global climate forcing, as evidenced by the effects of Mt. Agung (1963) and El Chichón (1982) aerosols on our computed global temperatures. Thus, if a very large volcanic eruption occurred in the next few years, it could significantly reduce the projected warming trend for several years. On the other hand, if there are no major volcanic eruptions in the remainder of the 1980s or the 1990s, that would tend to favor more rapid warming than obtained in scenarios B and C, which assumed an eruption in the mid 1990s of the magnitude of El Chichón. Interpretation of near term climate change will require monitoring of stratospheric aerosols, as well as solar irradiance.

Other climate forcings, such as changes in tropospheric aerosols or surface albedo, are also potentially significant (Appendix B), but probably are important mainly on a regional basis. Examples of changing aerosol abundance include the arctic haze, long-range transport of desert aerosols, and perhaps urban and rural aerosols of anthropogenic origin. Significant surface albedo variations may be associated with large scale deforestation and desertification, but available information on trends is not sufficiently quantitative for inclusion in our global simulations. It is desirable that calibrated long-term monitoring of tropospheric aerosols and surface albedo be obtained in the future.

6.3. *Ocean Heat Storage and Transport*

Our ocean model is based on the assumption that, for the small climate forcings of the past few decades and the next few decades, horizontal transport of heat by the ocean will not change significantly and uptake of heat perturbations by the ocean beneath the mixed layer will be at a rate similar to that of passive tracers simulated as a diffusive process. We believe that these assumptions give a global result which is as reliable as presently possible, given available knowledge and modeling abilities for the ocean; in any case this approach provides a first result against which later results obtained with dynamically interactive oceans can be compared.

However, we stress that our ocean model yields relatively smooth surprise-free temperature trends. It excludes the possibility of shifts in ocean circulation or in the rate of deep water formation. There is evidence in paleoclimate records that such ocean fluctuations have occurred in the past [*Broecker et al.*, 1985], especially in the North Atlantic, where, for example, a reduction in the rate of deep water formation could reduce the strength of the Gulf Stream and thus lead to a cooling in Europe. We caution that our ocean model assumptions exclude the possibility of such sudden shifts in regional or global climate.

We also stress the importance of measuring the rate of heat storage in the ocean. As discussed above and by *Hansen et al.* [1985], on the time scale of a few decades there is not necessarily a great difference in the surface temperature response for a low climate senitivity (say 1.5–2°C for doubled CO_2) and a high climate sensitivity (say 4–5°C for doubled CO_2). However, the larger climate sensitivity leads to a higher rate of heat storage in the ocean. Since theoretical derivations of climate sensitivity depend so sensitively on many possible climate feedbacks, such as cloud and aerosol optical properties [*Somerville and Remer*, 1984; *Charlson et al.*, 1987], the best opportunity for major improvement in our understanding of climate sensitivity is probably monitoring of internal ocean temperature. Such measurements would be needed along several sections crossing the major oceans. In principle, the measurements would only be needed at decadal intervals, but continuous measurements are highly desirable to average out the effect of local fluctuations.

6.4. *Initial Conditions*

Because of the long response time of the ocean surface temperature, the global surface temperature can be in substantial disequilibrium with the climate forcing at any given time. By initiating our experiments in 1958 after a long control run with 1958 atmospheric composition, we implicitly assume that the ocean temperature was approximately in equilibrium with the initial atmospheric composition. Our results could be significantly modified by a different assumption. For example, if there were substantial unrealized greenhouse warming in 1958 due to a steady increase of greenhouse forcing between the 1800s and 1958, incorporation of that disequilibrium in our initial conditions would have caused the global temperature to rise faster than it did in our experiments. We initiated our experiments in 1958 principally because that is when accurate CO_2 measurements began. However, 1958 also appears to be a good starting point to minimize the possibility of a major disequilibrium between the initial ocean surface temperature and the atmospheric forcing. Global temperature peaked about 1940 and was level or declined slightly in the two decades between 1940 and 1958. Regardless of whether the 1940 maximum was an unforced fluctuation of temperature or due to a maximum of some climate forcing, one effect of that warm period is to reduce and perhaps eliminate any unrealized greenhouse warming in 1958.

It would be useful to also carry out simulations which begin in say the 1800s, thus reducing uncertainties due to possible disequilibrium in the initial conditions. These experiments would be particularly appropriate for extracting empirical information on climate sensitivity from the observed warming in the past century. Such experiments were beyond the capability of our computer (circa 1975 Amdahl). Moreover, because of greater uncertainties in climate forcings before 1958, such experiments probably would not yield more reliable predictions of future climate trends.

6.5. *Summary*

Our model results suggest that global greenhouse warming will soon rise above the level of natural climate variability. The single best place to search for the greenhouse effect appears to be the global mean surface air temperature. If it rises and remains for a few years above an appropriate significance level, which we have argued is about 0.4°C for 99% confidence (3σ), it will constitute convincing evidence of a cause and effect relationship - a "smoking gun", in current vernacular.

Confirmation of the global warming will enhance the urgency of innumerable questions about the practical impacts of future climate change. Answers to these questions will depend upon the details of the timing, magnitude and global distribution of the changes of many climate parameters, information of a specificity which cannot presently be provided. Major improvements are needed in our understanding of the climate system and our ability to predict climate change.

We conclude that there is an urgent need for global measurements to improve knowledge of climate forcing mechanisms and climate feedback processes. The expected climate changes in the 1990s present at once a great scientific opportunity, because they will provide a chance to discriminate among alternative model representations, and a great scientific challenge, because of demands that will be generated for improved climate assessment and prediction.

Appendix A: Ocean Model and Ocean Data

The seasonal transport of heat in our ocean model is specified by the convergence (or divergence) of heat at each ocean gridpoint, determined from energy balance as the difference between the time rate of change of heat storage and the heat flux at the air sea interface. The heat storage is calculated from the *Robinson and Bauer* [1981] ocean surface temperatures, the Northern Hemisphere horizontal ice extent of *Walsh and Johnson* [1979], the Southern Hemisphere ice extent of *Alexander and Mobley* [1974], and mixed layer depths compiled from NODC bathythermograph data [*NOAA*, 1974]. The surface heat flux was saved from a two year run of Model II [*paper* 1] which used the above monthly ocean surface temperature as boundary conditions. Figure 1 of paper 2 shows this surface heat flux. The calculation of the ocean heat transport is described in more detail by *Russell et al.* [1985], whose Figure 5 shows the geographical distribution of the mixed layer depths for February and August. The global area-weighted value of the annual maximum mixed layer depth is 127 m.

The gross characteristics of the ocean surface heat flux and implied ocean heat transport appear to be realistic, with heat gain and flux divergence at low latitudes, and heat loss and flux convergence at high latitudes. A comprehensive comparison of the annual ocean heat transport by *Miller et al.* [1983] shows that the longitudinally integrated transport in each ocean basin is consistent with available knowledge of actual transports.

In our 100 year control run, there is no exchange of heat at the base of the mixed layer. In the experiments with varying atmospheric composition we mimic, as a diffusion process, the flux of temperature anomalies from the mixed layer into the thermocline. The thermocline, taken to be the water below the annual maximum mixed layer, is structured with eight layers of geometrically increasing thickness, with a total thickness of about 1000 m.

An effective diffusion coefficient, k, is estimated below the annual maximum mixed layer of each gridpoint using an empirical relation between the penetration of transient inert tracers and the local water column stability [*paper* 2], the latter being obtained from the annual mean density distribution calculated from *Levitus* [1982]. The resulting global distribution of k is shown in Figure 15a of paper 2. There is a low exchange rate ($k = 0.2$ cm^2/sec) at low latitudes and a high exchange rate in the North Atlantic and southern oceans where convective overturning occurs. Note that k is constant in time and in the vertical direction.

The ocean temperature and the ocean ice state in the transient experiments are computed based on energy balance. The specified converged ocean heat and the diffusion into the thermocline are deposited into or removed from the active mixed layer. The surface flux heats (or cools) the open ocean and ocean ice in proportion to their exposed areas. In addition there is a vertical exchange (conduction) of heat between the ocean and the ice above it.

When the surface fluxes would cool the mixed layer below -1.6°C, the mixed layer stays at -1.6°C and ice with 1 m thickness is formed growing horizontally, at a rate determined by energy balance. When the surface fluxes would warm the ocean above 0°C, the ocean stays at 0°C until all ice in the gridbox is melted horizontally. Conductive cooling at the ice/water interface thickens the ice if the ocean temperature is at -1.6°C. Leads are crudely represented by requiring that the fraction of open water in a gridbox not be less than $0.1/z_{ice}$, where z_{ice} is the ice thickness in meters [*paper 1*].

Appendix B: Radiative Forcings

Radiative forcing of the climate system can be specified by the global surface air temperature change ΔT_0 that would be required to maintain energy balance with space if no climate feedbacks occurred [*paper 2*]. Radiative forcings for a variety of changes of climate boundary conditions are compared in Figure B1, based on calculations with a 1-D radiative-convective (1-D RC) model [*Lacis et al.*, 1981]. The following formulae approximate the ΔT_0 from the 1-D RC model within about 1 percent for the indicated ranges of composition. The absolute accuracy of these forcings is of the order of 10% due to uncertainties in the absorption coefficients and approximations in the 1-D calculations.

CO_2: $\Delta T_0(x) = f(x) - f(x_0)$;

$$f(x) = \ln(1 + 1.2x + 0.005x^2 + 1.4\times10^{-6}x^3);$$

$$x_0 = 315 \text{ ppmv}, x \leq 1000 \text{ ppmv}$$

CCl_2F_2: $\Delta T_0(x) = 0.084(x-x_0)$; $x-x_0 \leq 2$ ppbv

CCl_3F: $\Delta T_0(x) = 0.066(x-x_0)$; $x-x_0 \leq 2$ ppbv

CH_4: $\Delta T_0 = g(x,y_0) - g(x_0,y_0)$

N_2O: $\Delta T_0 = g(x_0,y) - g(x_0,y_0)$

$x,y \leq 5$ ppmv

where

$$g(x,y) = \frac{0.394x^{0.66} + 0.16xe^{-1.6x}}{1+0.169x^{0.62}} + 1.556\ln\left[1+\frac{y^{0.77}(109.8+3.5y)}{100+0.14y^2}\right]$$

$$-0.014\ln[1+0.636(xy)^{0.75} + 0.007x(xy)^{1.52}];$$

H_2SO_4 aerosols (20km): $\Delta T_0(\tau) = -5.8\tau$; $\tau(\lambda = 550\text{nm}) \leq 0.2$

H_2SO_4 aerosols (0-2km): $\Delta T_0(\tau) = -6.5\tau$; $\tau(\lambda = 550\text{nm}) \leq 0.2$

Solar irradiance: $\Delta T_0(x) = 0.67x$; $x = \Delta S_0(\%) \leq 1\%$

Land albedo: $\Delta T_0(x) = -0.12x$;
$x = \Delta$ albedo of land area ≤ 0.1

Trace gas scenarios

Trace gas trends beginning in 1958 (when accurate measurements of CO_2 began) were estimated from measurement data available in early 1983 when we initiated our transient simulations. References to the measurements are given in *Shands and Hoffman* [1987]. Figure B2 summarizes the estimated decadal increments to global greenhouse forcing. The forcings shown by dotted lines in Figure B2 are speculative; their effect was included in scenario A, but excluded in scenarios B and C. The CH_4 forcing in the 1980s represents a 1.5% yr^{-1} growth rate; recent data [*Bolle et al.*, 1986] suggests that a 1.1% yr^{-1} growth rate probably is more realistic.

Specifically, in scenario A CO_2 increases as observed by Keeling for the interval 1958-1981 [*Keeling et al.*, 1982] and subsequently with 1.5% yr^{-1} growth of the annual increment. CCl_3F (F11) and CCl_2F_2 (F12) emissions are from reported rates (CMA, 1982) and assume 3% yr^{-1} increased emission in the future, with atmospheric lifetimes for the gases of 75 and 150 years, respectively. CH_4, based on estimates given by *Lacis et al.* [1981], increases from 1.4 ppb in 1958 at a rate of 0.6% yr^{-1} until 1970, 1% yr^{-1} in the 1970s and 1.5% yr^{-1} thereafter. N_2O increases according to the semi-empirical formula of *Weiss* [1981], the rate being 0.1% yr in 1958, 0.2% yr^{-1} in 1980, 0.4% yr^{-1} in 2000 and 0.9% yr^{-1} in 2030. Potential effects of several other trace gases (such as O_3, stratospheric H_2O, and chlorine and fluorine compounds other than CCl_3F and CCl_2F_2) are approximated by multiplying the CCl_3F and CCl_2F_2 amounts by two.

In scenario B the growth of the annual increment of CO_2 is reduced from 1.5% yr^{-1} today to 1% yr^{-1} in 1990, 0.5% yr^{-1} in 2000 and 0 in 2010; thus after 2010 the annual increment in CO_2 is constant, 1.9 ppm yr^{-1}. The annual growth of CCl_3F and CCl_2F_2 emissions is reduced from 3% yr^{-1} today to 2% yr^{-1} in 1990, 1% yr^{-1} in 2000 and 0 in 2010. The methane annual growth rate decreases from 1.5% yr^{-1} today to 1.0% in 1990 and 0.5% yr^{-1} in 2000. N_2O increases are based on the formula of *Weiss* [1981], but the parameter specifying annual growth in anthropogenic emission decreases from 3.5% today to 2.5% in 1990, 1.5% in 2000 and 0.5% in 2010. No increases are included for other chlorofluorocarbons, O_3, stratospheric H_2O or any other greenhouse gases.

In scenario C the CO_2 growth is the same as in scenarios A and B through 1985; between 1985 and 2000 the annual CO_2 increment is fixed at 1.5 ppm yr^{-1}; after 2000 CO_2 ceases to increase, its abundance remaining fixed at 368 ppm. CCl_3F and CCl_2F_2 abundances are the same as in scenarios A and B until 1990; thereafter CCl_3F and CCl_2F_2 emissions decrease linearly to zero in 2000. CH_4 abundance is the same as in scenarios A and B until 1980; between 1980 and 1990 its growth rate is 1% yr^{-1}; between 1990 and 2000 its growth rate is 0.5% yr^{-1}; after 2000 CH_4 ceases to increase, its abundance remaining fixed at 1916 ppb. As in scenario B, no increases occur for the other chlorofluorocarbons, O_3, stratospheric H_2O or any other greenhouse gases.

Stratospheric aerosol scenarios

The radiative forcing due to stratospheric aerosols depends principally upon their optical thickness at visible wavelengths, their opacity in the thermal infrared region, and their global distribution. Because of the small size of long-lived stratospheric aerosols, their effect on planetary albedo generally exceeds their effect on infrared transmission [*Hansen et al.*, 1980]. Thus the most important aerosol radiative parameter is the optical thickness at visible wavelengths, τ. We base the estimated τ before El Chichón primarily on solar transmission measurements at Mauna Loa (Mendonca, 1979) together with calculations with

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a three-dimensional tracer model [*Russell and Lerner*, 1981].

The measured optical depth at Mauna Loa, after subtraction of the mean 1958-1962 value which is assumed to represent the local background value, is shown as the light line in Figure B3. An arbitrary amount of tracer substance was introduced in the stratosphere of the tracer model at the time and location of the volcanic eruptions of Agung (1963), Awu (1966), Fernandina (1968) and Fuego (1974). The computed amount of tracer at Mauna Loa was then multiplied by the scale factor required such that the computed transmission equaled the mean measured transmission at Mauna Loa in the two years following the eruption; the modeled aerosol opacity is illustrated by the heavier line in Figure B3. The tracer model thus defined the global distribution of aerosol optical depth for the period 1958-1979.

The aerosol optical depths for El Chichón, based on early reports (McCormick, private communication), later published by *McCormick et al.*, [1984], were specified as follows. For the first six months after the eruption the opacity was uniformly distributed between the equator and 30°N, increasing linearly from $\tau=0$ at the time of eruption to $\tau=0.25$ three months after the eruption and remaining constant for the next three months. Subsequently the opacity was uniform from 90°N to 30°N and from 30°N to 90°S, but with two times greater τ in the northern region than in the southern region. Beginning 10 months after the eruption τ decayed exponentially with a 12 month time constant.

The optical properties of the stratospheric aerosols before 1982 are based on measurements of Agung aerosols. The size distribution we used is that given by *Toon and Pollack* [1976], which is based on measurements by *Mossop* [1964]; it has mean effective radius and variance [*Hansen and Travis*, 1974] of $r_{eff} = 0.2\mu m$ and $v_{eff} = 0.6$. These aerosols are assumed to be spheres of sulfuric acid solution (75% acid by weight) with refractive index given by *Palmer and Williams* [1975]. We used size data for the El Chichón aerosol based on measurements of *Hoffman and Rosen* [1983]. Their May 1982 data had $r_{eff} = 1.4\mu m$, $v_{eff} = 0.4$, while their October 1982 data had $r_{eff} = 0.5\mu m$, $v_{eff} = 0.15$. We interpolated linearly between these two size distributions for the six month period April 1982 to October 1982, and thereafter used the small particle (October 1982) size distribution. These various size distributions yield the same cooling at the earth's surface as a function of τ ($\lambda = 550nm$), within a few percent, as computed with the 1-D RC model, but the large particles cause a greater stratospheric heating. For example, the May 1982 distribution yields a warming of 5°C at 23km, the October 1982 distribution yields 2°C, and the *Mossop* [1964] aerosols yields 1.5°C.

An extensive measurement campaign was mounted after the El Chichón eruption in 1982, which will allow a more precise calculation of the geographical and altitute distribution of the radiative forcing than for any previous volcano. We are working with J. Pollack and P. McCormick to make use of the full data now available for a comprehensive study of the climate impact in that period. However, the scenarios in our present simulations were defined in early 1983 when only sketchy data on the El Chichón aerosols was available, so the uncertainty in the aerosol forcing after El Chichón in our present simulations is comparable to that in the prior years.

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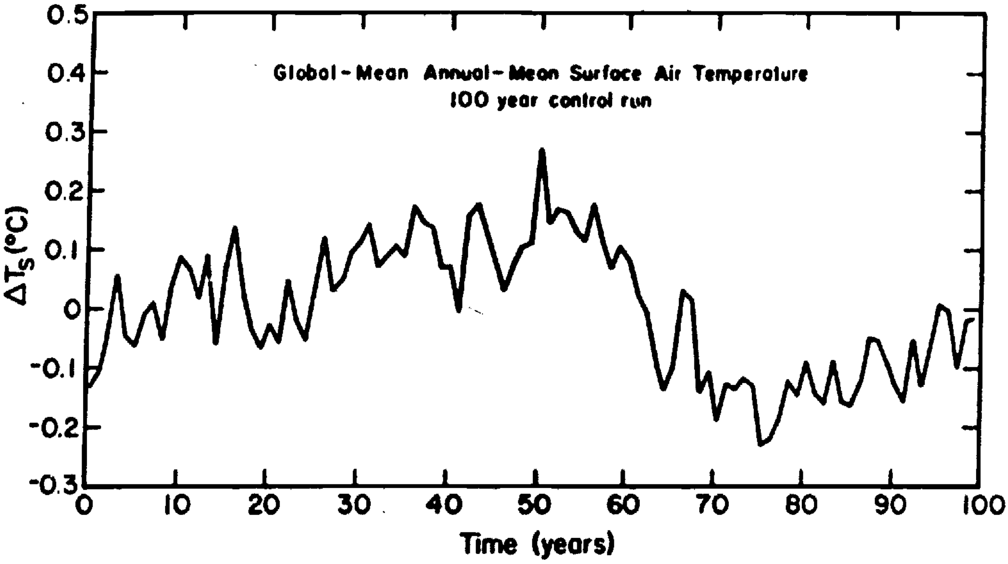


Fig. 1. Global-mean annual-mean surface air temperature trend in the 100 year control run.

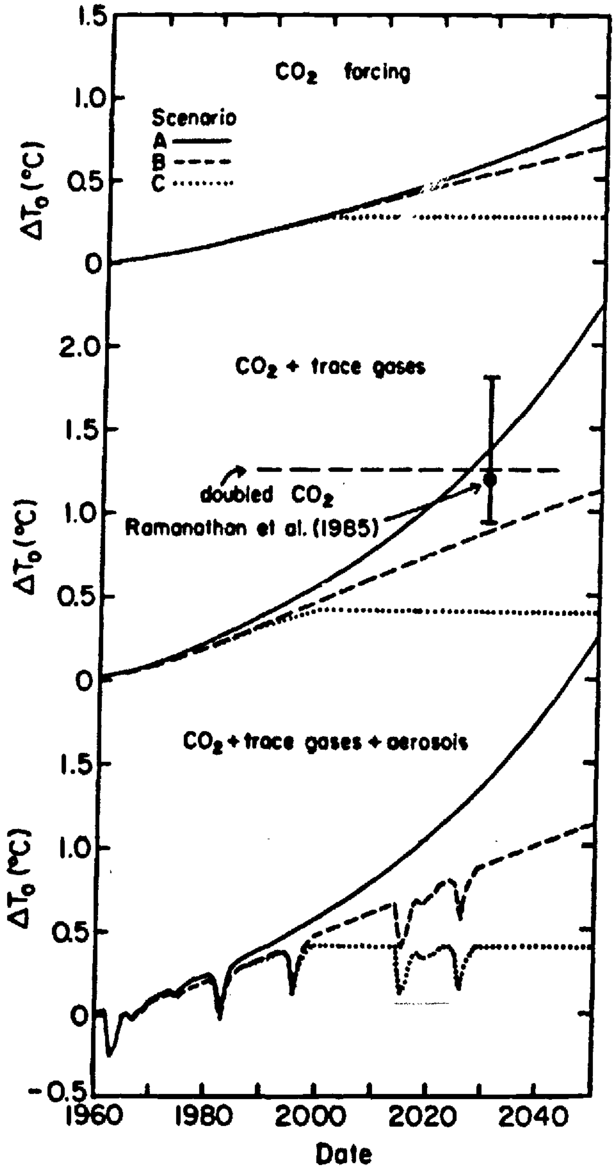


Fig. 2. Greenhouse forcing for trace gas scenario A, B and C, as described in the text. ΔT_0 is the equilibrium greenhouse warming for no climate feedbacks. The doubled CO_2 level of forcing, $\Delta T_0 \approx 1.25$°C, occurs when the CO_2 and trace gases added after 1958 provide a forcing equivalent to doubling CO_2 from 315 ppm to 630 ppm. The CO_2 + trace gas forcing estimated by *Ramanathan et al.* [1985] for 2030 is also illustrated.

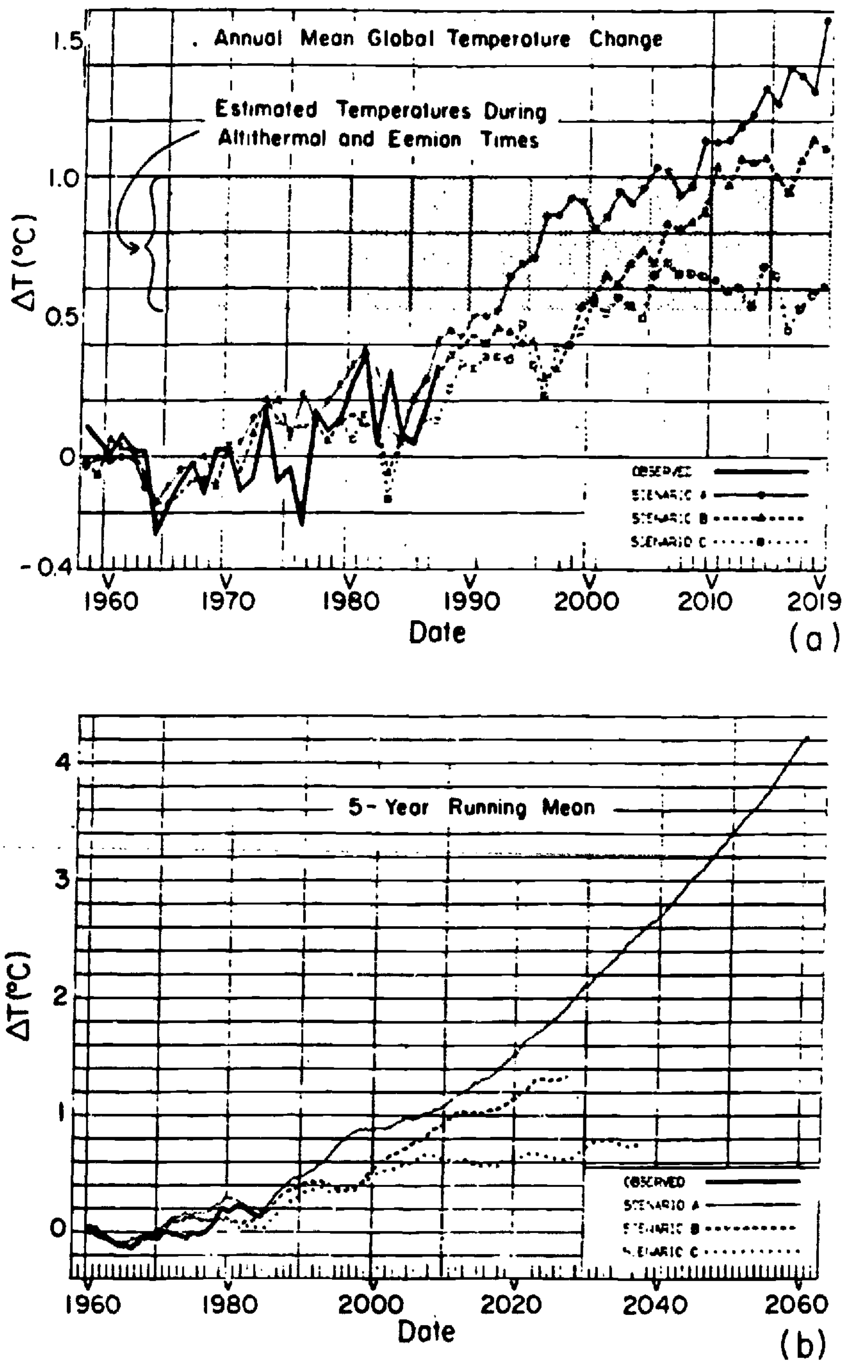


Fig. 3. Annual mean global surface air temperature computed for scenarios A, B and C. Observational data is from *Hansen and Lebedeff* [1987, 1988]. The shaded range in part (*a*) is an estimate of global temperature during the peak of the current and previous interglacial periods, about 6,000 and 120,000 years before present, respectively. The zero point for observations is the 1951–1980 mean [*Hansen and Lebedeff*, 1987]; the zero point for the model is the control run mean.

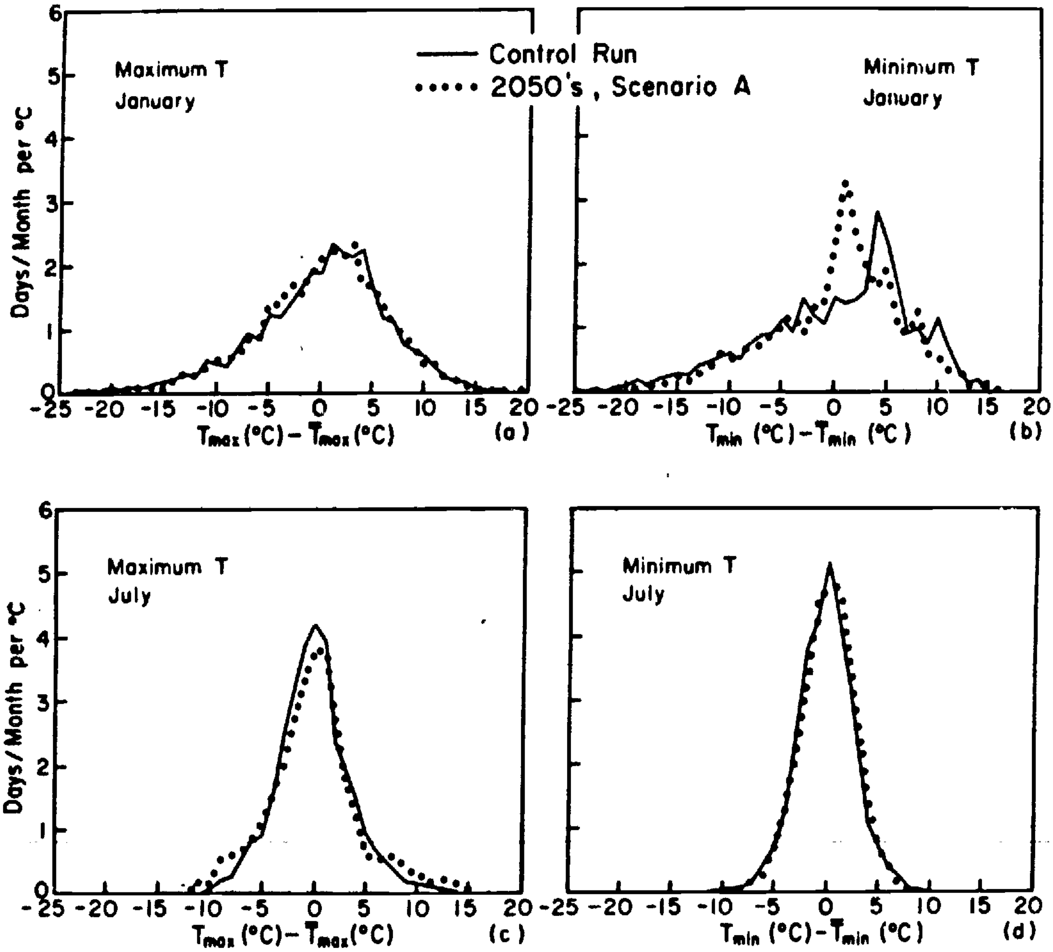


Fig. 4. Distribution of daily maximum and daily minimum temperatures in January and July for 10 gridboxes (latitudes 31°N to 47°N, longitudes 75°W to 125°W) approximately covering the United States. The solid line represents years 92–100 of the control run and the dotted line if for years 2050–2059 of scenario A. The mean temperature at each gridbox is subtracted out first, before computing the mean distribution for the 10 gridboxes.

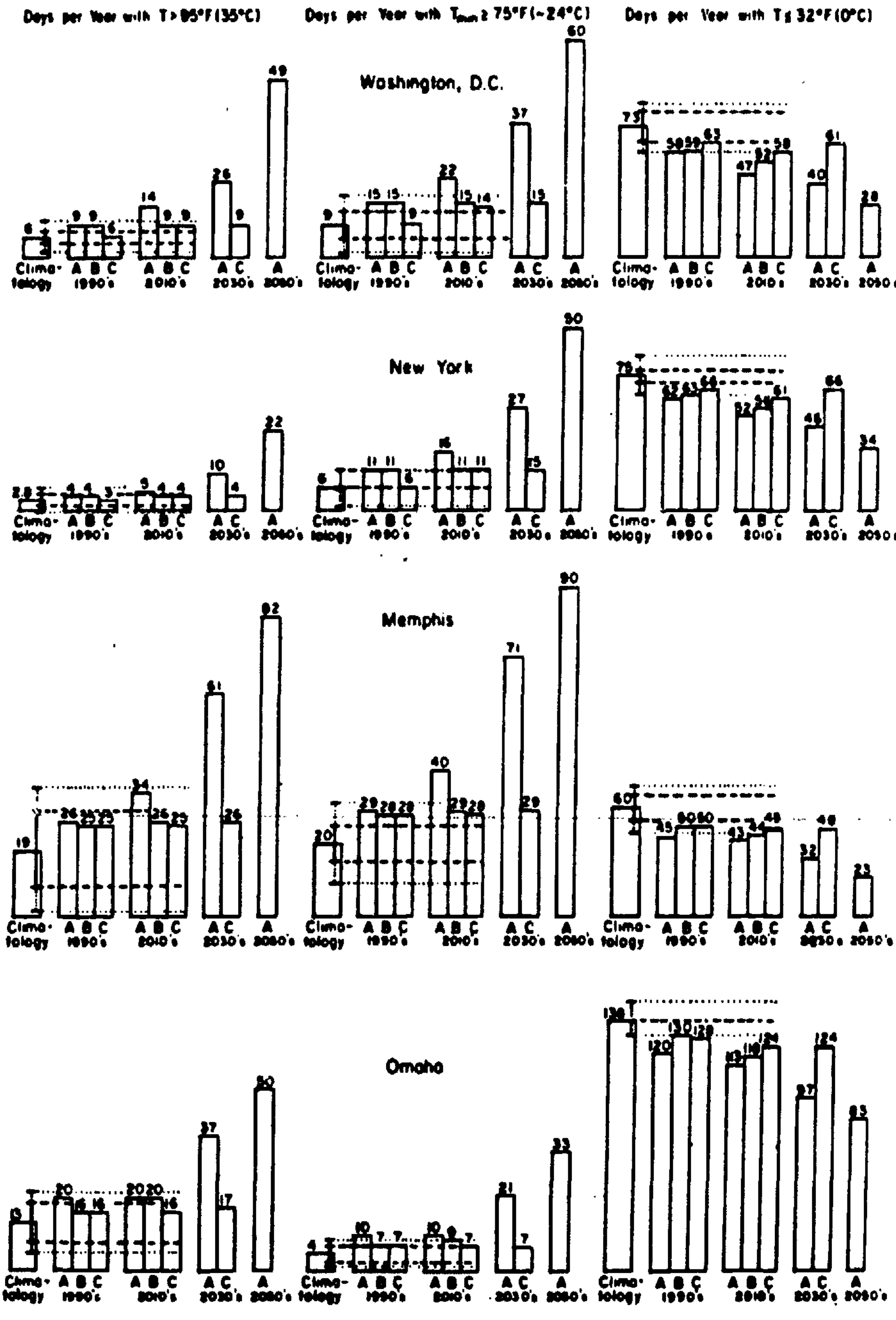


Fig. 5. Climatology and model-based estimates of future frequency of extreme temperature in several cities specifically: days with maximum temperature above 95°F (35°C), days with minimum temperature above 75°F (≈ 24°C), and days with minimum temperature below 35°F (0°C). Climatology is for the three decades 1950–1979; the long and short bars (and the dotted and dashed horizontal lines) specify the interannual and interdecadal variability (standard deviation), respectively, for these 30 years of data. A, B and C represent trace gas scenarios A, B and C. The vertical scale for days with T ≤ 32°F (0°C) is a factor two less than the scale for the other two quantities.

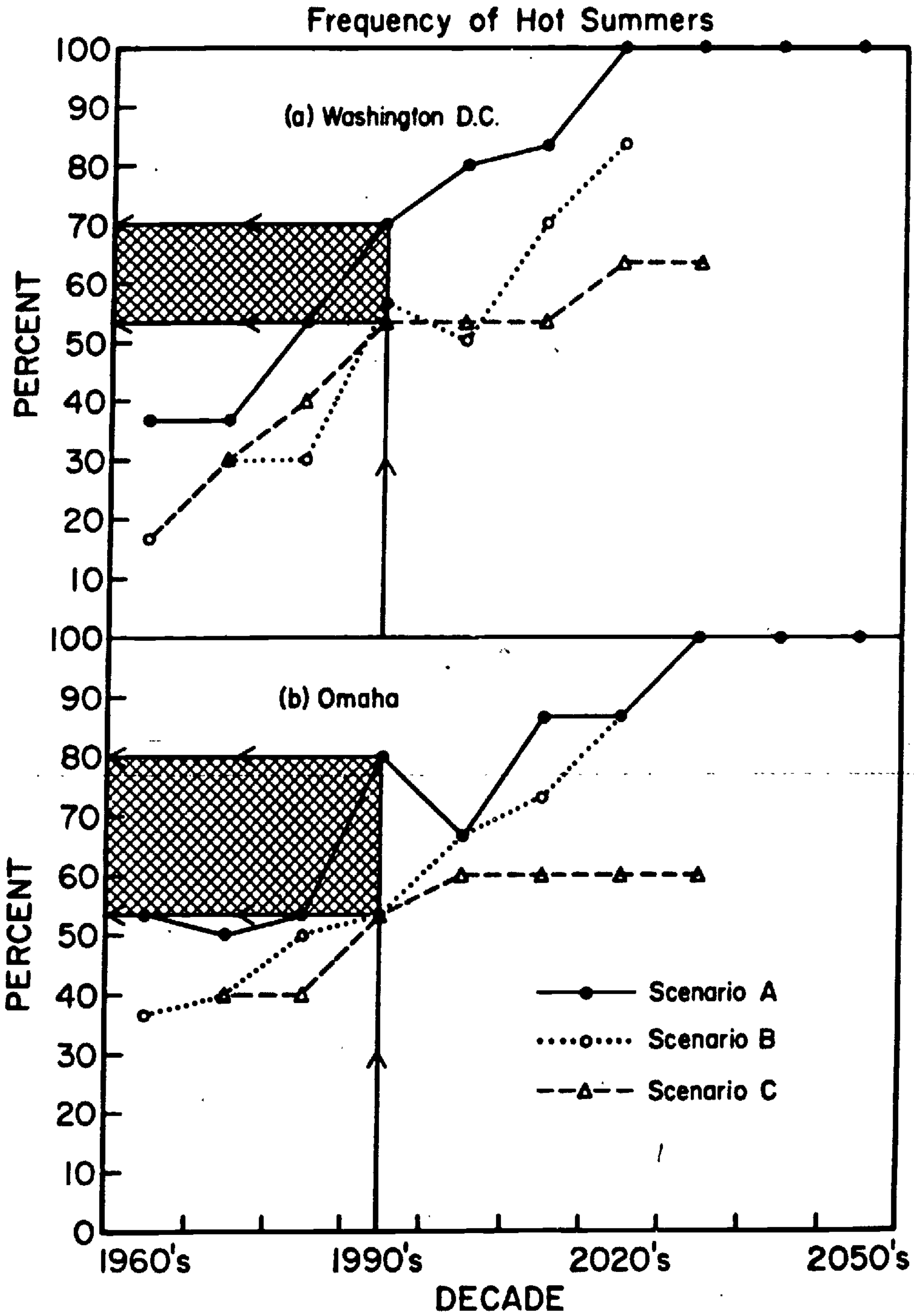


Fig. 6. Estimate of the probability of the summer being "hot", shown for two locations for scenarios A, B and C. A "hot" summer is one in which the mean temperature exceeds a value which was chosen such that one-third of the summers were "hot" in 1950–1979 observations. The estimated probability for hot summers in the 1990s is shown by the shaded region for the range of scenarios.

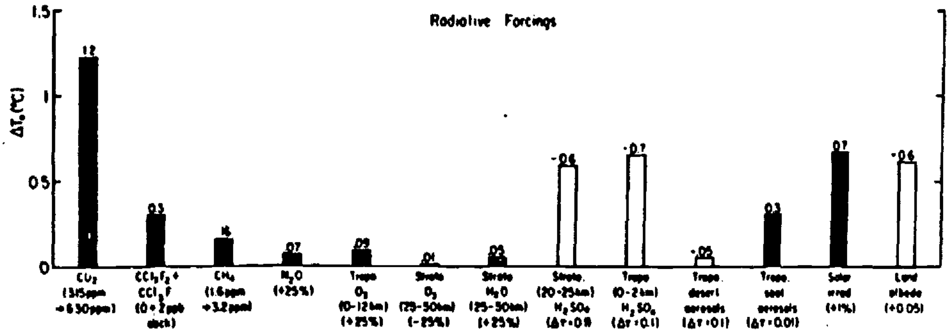


Fig. B1. Global mean radiative forcing of the climate system for arbitrary changes of radiative parameters. ΔT_o is the temperature change at equilibrium ($t \rightarrow \infty$) computed with a 1-D RC model for the specified change in radiative forcing parameter, with no climate feedbacks included; ΔT_o must be multiplied by a feedback factor f to get the equilibrium surface temperature change including feedback effects [paper 2]. Tropospheric aerosols are all placed in the lower two kilometers of the atmosphere; the desert aerosols have effective radius $r_{eff} = 2$ μm and single scattering albedo $\omega = 0.8$ at wavelength $\lambda = 550$nm, while the soot aerosols have $r_{eff} = 1$ μm and $\omega = 0.5$. The land albedo change of 0.05 is implemented via a change of 0.015 in the surface albedo, corresponding to 30% land cover.

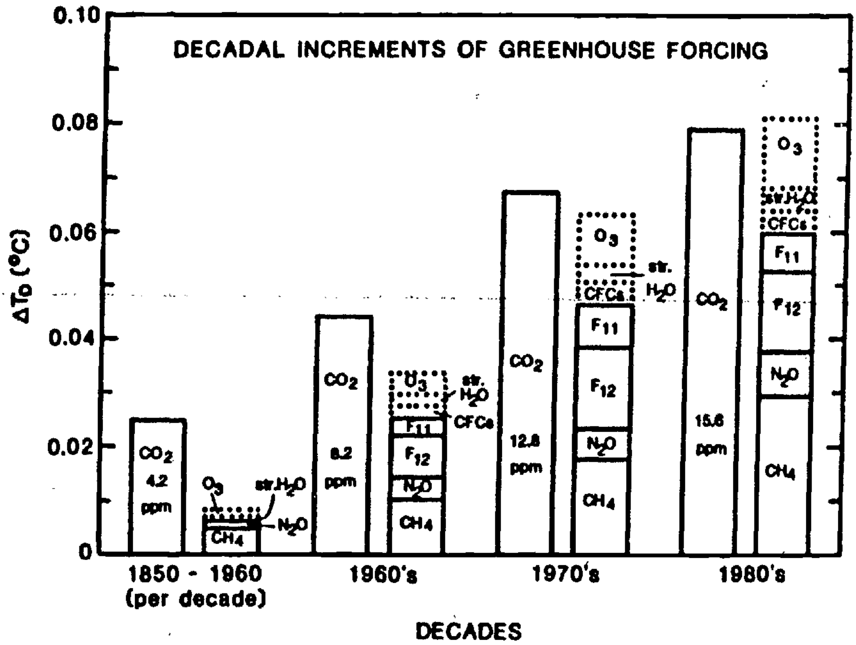


Fig. B2. Estimated decadal additions to global mean greenhouse forcing of the climate system. ΔT_o is defined in the caption of Fig. B1. Forcings shown by dotted lines are highly speculative.

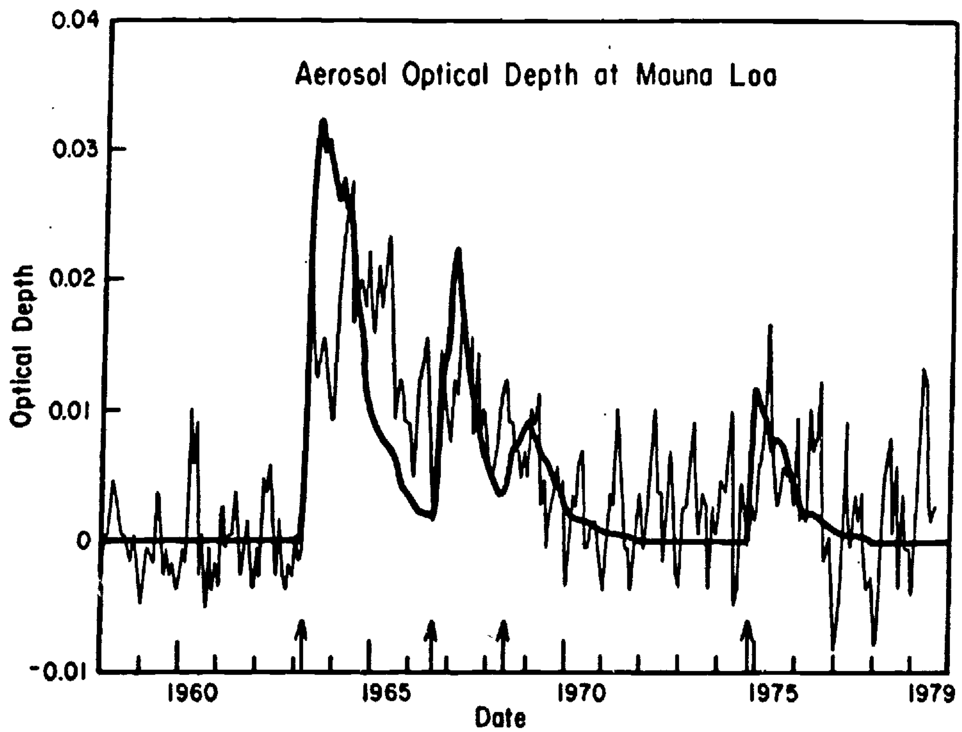


Fig. B3. Aerosol optical depth measured at Mauna Loa (light line) after subtraction of the mean value for 1958–1962. The heavy line is the optical depth at Mauna Loa obtained from the three-dimensional tracer model, as discussed in the text. The arrows mark the times of eruption of Agung, Awu, Fernandina and Fuego, respectively.

Plate 1. Interannual variability (standard deviation) of temperature in the 100 year control run (left side) and as estimated from observations (right side). (*a*), (*b*), (*c*) and (*d*) show the interannual variability of surface air temperature, and (e) and (*f*) show the interannual variability of the longitude-integrated upper air temperature. (*b*) and (*d*) are based on 1951–1980 observations at meteorological stations analyzed by *Hansen and Lebedeff* [1987]. (*f*) is based on 1958–1985 radiosonde data analyzed by *Angell* [1986]. Regions without data are black.

Plate 2. Left side: decadal mean temperature change obtained for scenario B, relative to the control run, for the decades 1980s, 1990s and 2010s. Right side: ratio of the computed temperature change to the interannual variability of the annual mean temperature in the 100 year control run (Plate 1*a*).

Plate 3. Left side: decadal mean temperature change for scenario B as a function of latitude and season, for the decades 1980s, 1990s and 2010s. Right side: ratio of the computed temperature change to the interannual variability of the monthly mean temperature in the 100 year control run (Plate 1*c*)

Plate 4. Left side: decadal mean temperature change for scenario B as a function of pressure and latitude, for the decades 1980s, 1990s and 2010s. Right side: ratio of the computed temperature change to the interannual variability of the annual mean temperature in the 100 year control run (Plate 1*e*).

Plate 5. Simulated June–July–August (left side) and December–January–February temperature anomalies in the 1990s, compared to the 100 year control run with 1958 atmospheric composition.

Plate 6. Simulated July surface air temperature anomalies for six individual years of scenario B, compared to the 100 year control run with 1958 atmospheric composition.

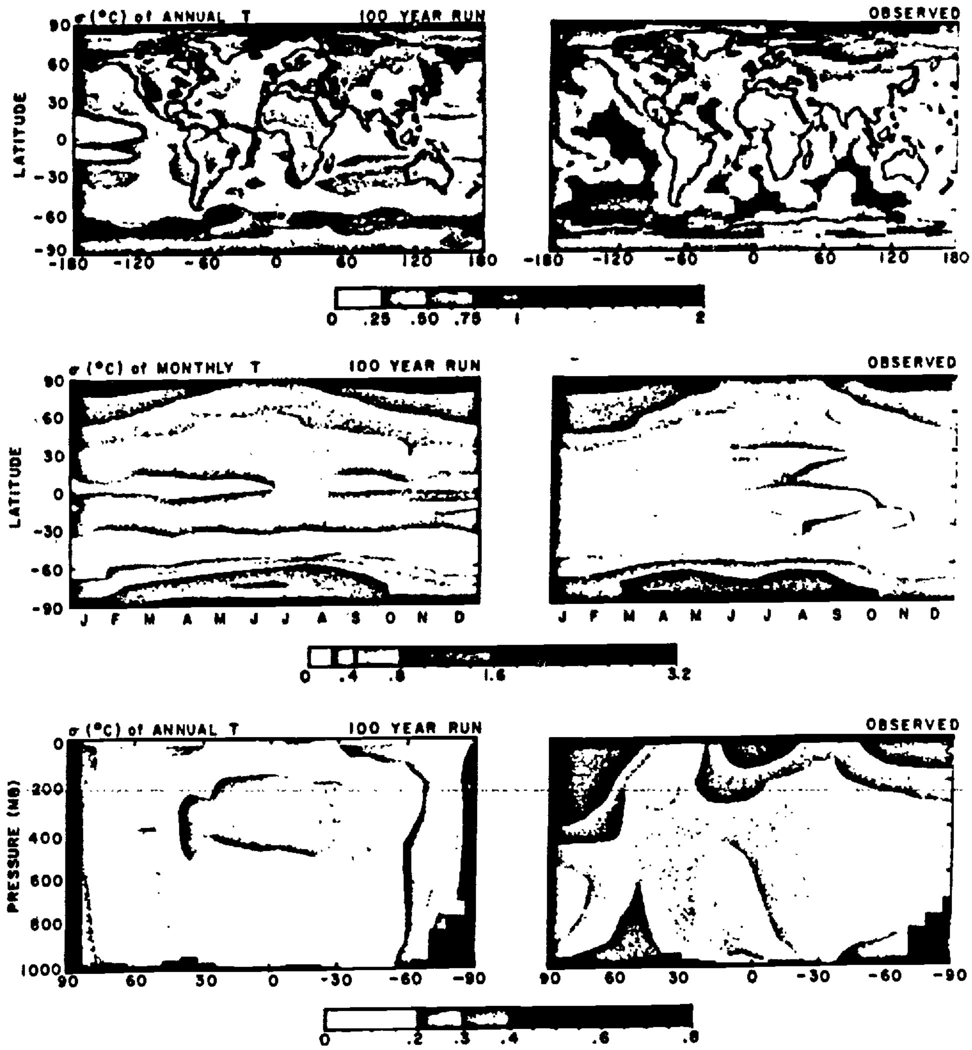
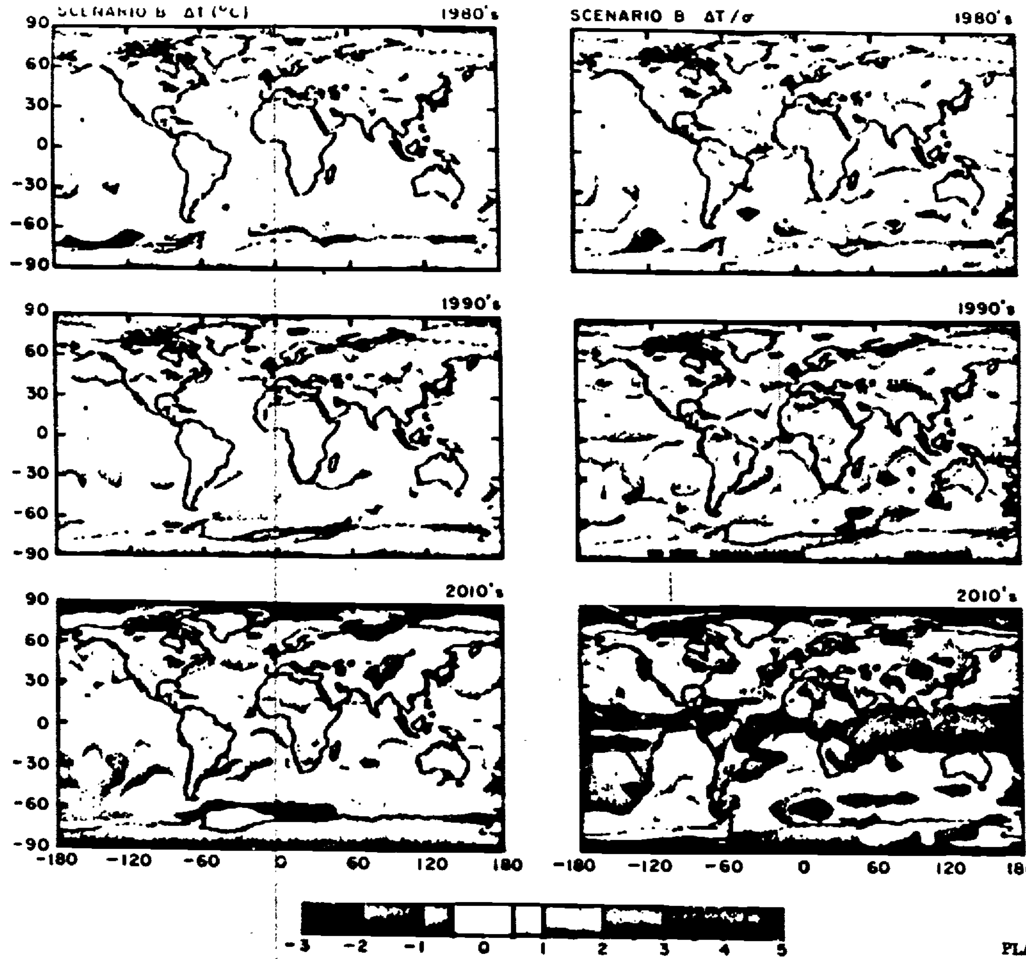

σ (°C) of ANNUAL T
100 YEAR RUN
OBSERVED
LATITUDE
0 .25 .50 .75 1 2
σ (°C) of MONTHLY T
100 YEAR RUN
OBSERVED
LATITUDE
J F M A M J J A S O N D
0 .4 .8 1.6 3.2
σ (°C) of ANNUAL T
100 YEAR RUN
OBSERVED
PRESSURE (MB)
0 .2 .3 .4 .6 .8

PLATE 1



SCENARIO B ΔT (°C)
SCENARIO B ΔT / σ
1980's
1990's
2010's
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
-3
-2
-1
0
1
2
3
4
5

PLATE 2

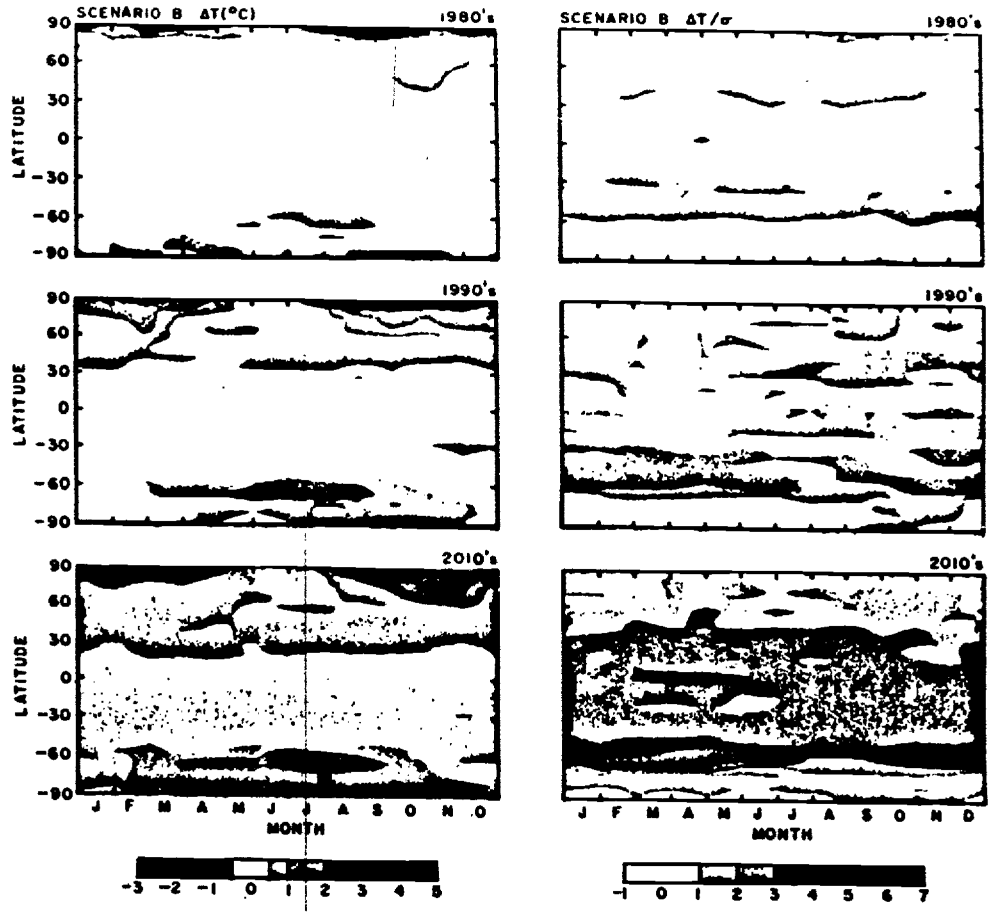

SCENARIO B ΔT(°C)
1980's
1990's
2010's
LATITUDE
90 60 30 0 -30 -60 -90
J F M A M J J A S O N D
MONTH
-3 -2 -1 0 1 2 3 4 5
SCENARIO B ΔT/σ
-1 0 1 2 3 4 5 6 7

PLATE 3

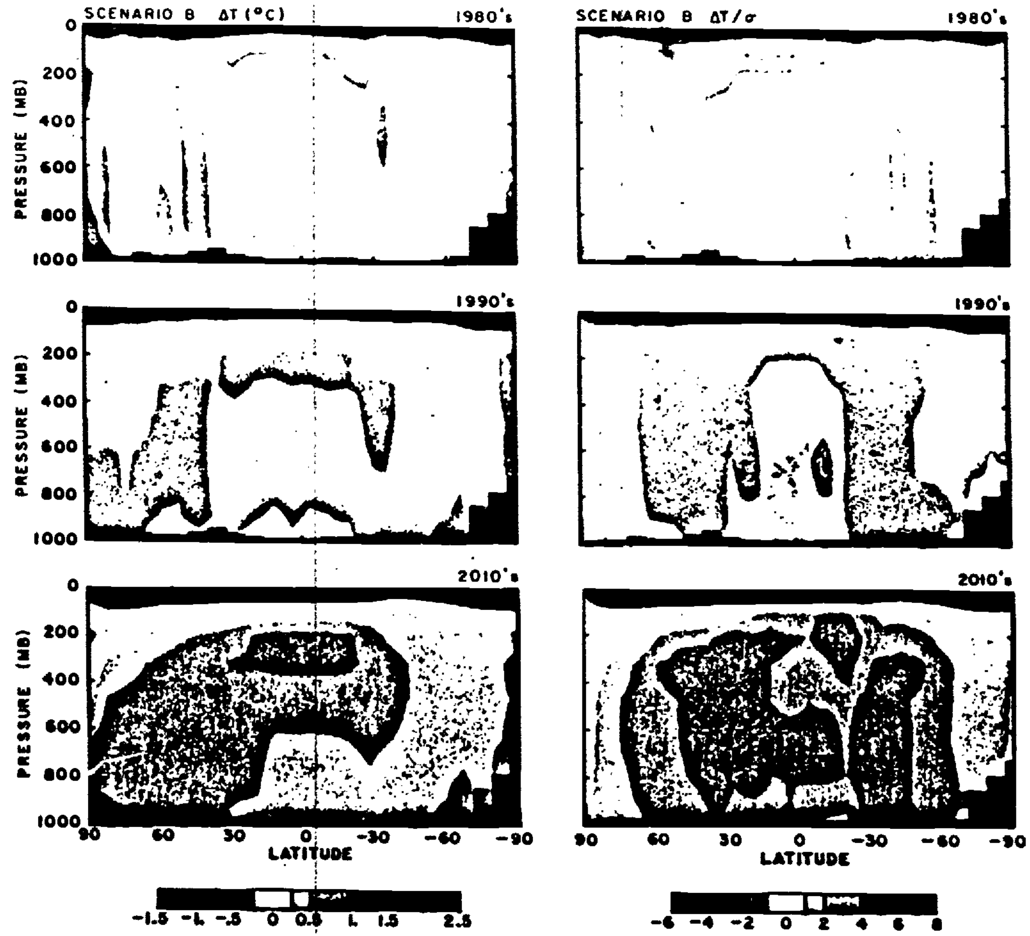

SCENARIO B ΔT (°C)
1980's
SCENARIO B ΔT/σ
1980's
1990's
1990's
2010's
2010's
PRESSURE (MB)
0
200
400
600
800
1000
90 60 30 0 -30 -60 -90
LATITUDE
-1.5 -1. -.5 0 0.5 1. 1.5 2.5
-6 -4 -2 0 2 4 6 8

PLATE 4

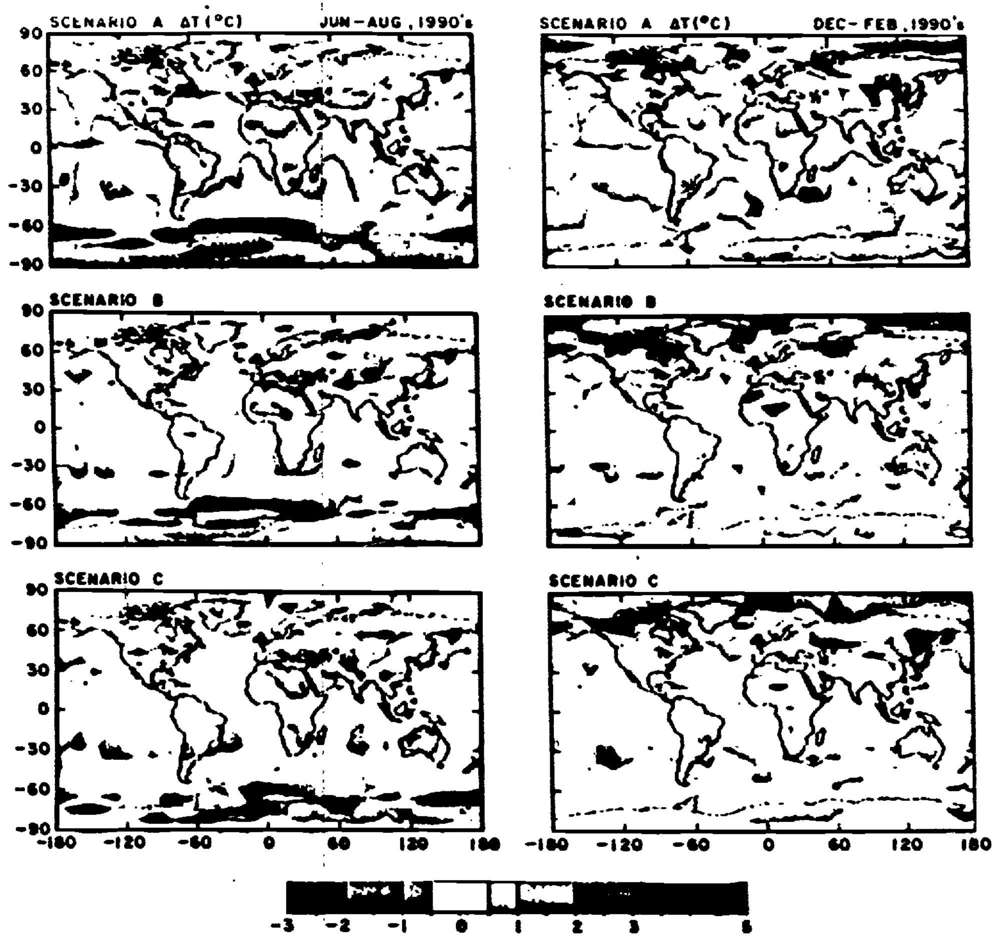

SCENARIO A ΔT(°C)
JUN-AUG, 1990's
SCENARIO A ΔT(°C)
DEC-FEB, 1990's
SCENARIO B
SCENARIO B
SCENARIO C
SCENARIO C
90 60 30 0 -30 -60 -90
-180 -120 -60 0 60 120 180
-3 -2 -1 0 1 2 3 5

PLATE 5

SCENARIO B

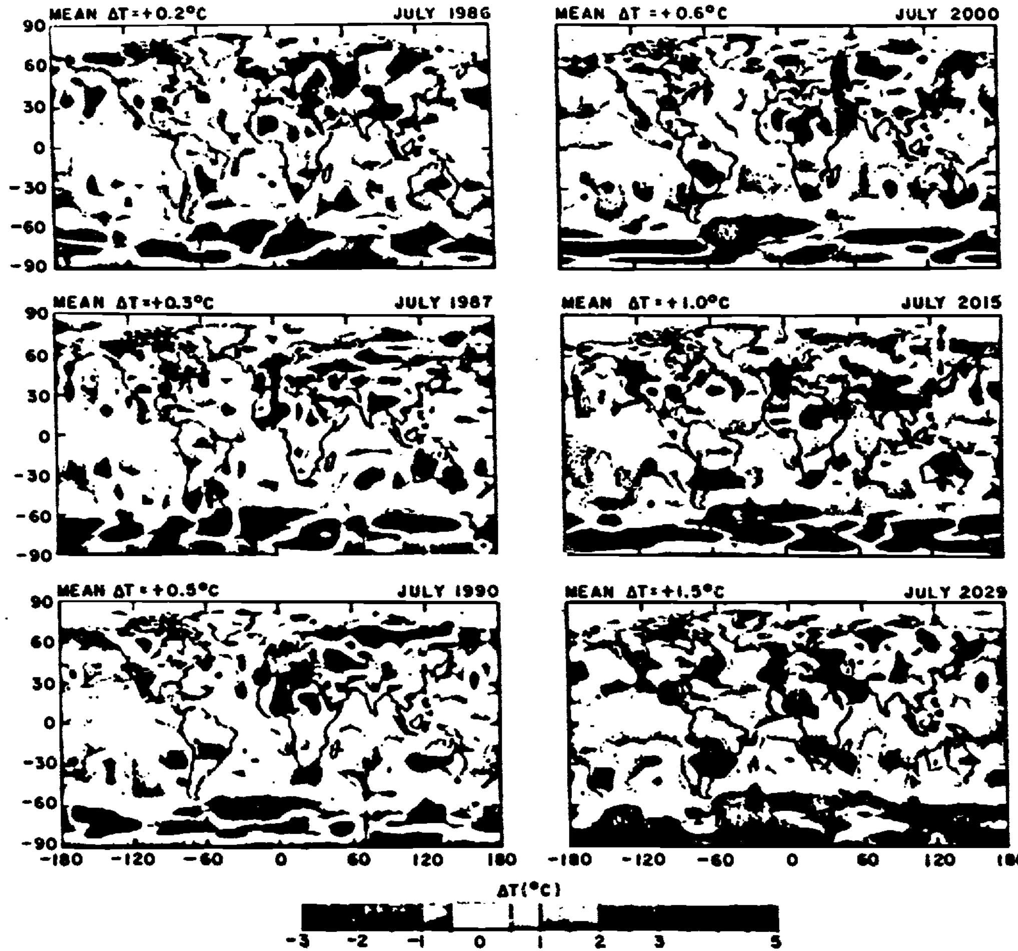


PLATE 6

Senator WIRTH. Fine. Thank you very much, Dr. Hansen. I think what we will do is run through the whole panel, if we might. If we might then go in the order in which I introduced the witnesses; Mr. Oppenheimer, Mr. Woodwell, Mr. Manabe, Mr. Dudek, and Mr. Moomaw.

STATEMENT OF DR. MICHAEL OPPENHEIMER, SENIOR SCIENTIST, ENVIRONMENTAL DEFENSE FUND

Dr. OPPENHEIMER. Thank you, Mr. Chairman. My name is Dr. Michael Oppenheimer. I'm an atmospheric physicist and senior scientist with the Environmental Defense Fund.

Mr. Chairman, it is hot out today and unless we change our ways of producing energy, as we have just heard, it is going to continue to get hotter.

I would like to thank the committee for giving us the opportunity at this particularly appropriate time to testify about a recent report developing policies for responding to climatic change, which I will refer to as the Bellagio Report published two weeks ago by the World Meteorological Organization and the United Nations Environment Program. I participated, along with Dr. Woodwell, in the preparation of that report.

This project that led to the Bellagio Report was developed in the wake of the publication in 1985 of a report, sometimes called the Villach 1985 Report also by UNEP and WMO, in which experts on climate from around the world produced a consensus that global warming, due to the emissions of greenhouse gases, was indeed underway. An examination of policy options was recommended. The Bellagio Report based on deliberations at two meetings by scientists and policy makers found that the time for action to respond to the impending warming is now.

In particular the report recommends several steps to be undertaken immediately with the goal of slowing global warming. Other measures to cushion the consequences of unavoidable change and to develop a coordinated international response are also recommended in the report, including consideration of an international convention or law of the atmosphere.

In my personal opinion greenhouse warming presents the most important global challenge of the next few decades on a par with defense, disarmament and economic issues. With warming apparently now measurable, as we have just heard, we are already playing catch-up ball. The midwest drought is a warning. Whether or not it is related to global changes, it provides a small taste of the dislocation society will face with increasing frequency if we fail to act. If measures are not undertaken soon to limit the warming, humans face an increasingly difficult future while many natural ecosystems may have no future at all.

To illustrate the magnitude of the problem, I was going to briefly describe the greenhouse warming. I'm sure most of you have heard about it, so I don't need to repeat it. But it is due to the emissions of a variety of gases into the atmosphere which trap heat and lead to a warming of the surface. Primary among those is carbon dioxide. And remember also that the sea level will rise in lock step with the increasing temperature due to the expansion of the oceans and the melting of land ice. As long as the amounts of greenhouse gases increase in the atmosphere, this process will continue unabated.

There will be no winners in this world of continuous change, only a globe full of losers. Today's beneficiaries of change will be tomorrow's victims as any advantages of the new climate roll past them like a fast moving wave. There will be a limited ability to adapt because our goals for adaptation will have to change continuously. The very concept of conservation on which environmentalism in this country was originally built does not exist in a world which may change so fast that ecosystems, which are slow to adjust, will wither and die.

The technical findings of the Villach-Bellagio workshops include the following. Global mean temperature will likely rise at about 0.6 degrees Fahrenheit per decade and sea level at about 2.5 inches per decade over the next century. As we have heard, the temperature trend will be more extreme at the higher latitudes. These rates are three to six times recent historical rates. By early in the next century, the world could be warmer than at any time in human experience. Furthermore, as long as greenhouse gases continue to grow in the atmosphere, there is no known natural limit to the warming short of catastrophic change. Thus, at some point these emissions must be limited.

Because the oceans are slow to heat, there is a lag between emissions and full manifestation of corresponding warming, a lag which some estimate at 40 years. The world is now 1 degree Fahrenheit warmer than a century ago and may become another 1 or more degrees warmer even if conditions are curtailed today. These changes are effectively irreversible because greenhouse gases are long-lived. We cannot go back if we don't like the new climate. So, action to slow the warming must be taken before full consequences of current emissions are manifest and understood.

This already committed warming means some adaptation measures such as sea defense and even coastal abandonment are inevitable. But effective adaptation will be costly and for many nations, such as Bangladesh for instance, infeasible. In fact, it will be infeasible in some parts of the United States.

The natural environment cannot adapt effectively to such rapid changes. The impending warming must be viewed as a disaster for natural ecosystems. The mountaintop declines of red spruce in the eastern United States, for instance, which are generally ascribed to air pollution or local climatic variability, pale in comparison to the scope of change impending if warming continues. For instance, one model by Dr. Schugard at the University of Virginia predicts essentially biomass crashes in southeast pine forests over the next 40 years if warming continues with declines of up to 40 percent occurring over only decadal periods. The recent dispute over oil exploration in the Arctic National Wildlife Refuge may be beside the point if the Arctic ecosystem is driven off the north coast of Alaska by climatic change.

If climate changes rapidly, agriculture and water resources may be stressed. Even if global food supplies are maintained, one need only look to the current great plains' drought to see the human and economic cost associated with hot, dry weather in the grain belt. Weather of this sort we can expect with increasing frequency in the future.

Although some change is inevitable and, in fact, appears to be already underway, unacceptable warming is not inevitable if action is begun now. Every decade of delay and implementation of greenhouse gas abatement policies ultimately adds perhaps a degree Fahrenheit of warming and no policy can be fully implemented immediately in any event.

The experts assessing this situation at Bellagio thought that the limitation of warming to recent historical rates of about 0.2° Fahrenheit per decade for some finite time would at least give societies and natural ecosystems a fighting chance at adjustment. But unlimited warming at any rate is ultimately problematic.

I hasten to say that the foregoing picture in some sense is good news. The bad news is that climate change may not occur smoothly. Rather, it could occur discontinuously which would render fruitless any attempts at planned adaptation. The advent of the ozone hole should make us cautious in assuming that atmospheric change will be gradual.

My testimony contains a list of policy recommendations from the Bellagio Report, but let me make only one point. With permission of the Chairman, I'll use the figure over here.

Slow warming at an acceptable rate—well, let me describe these two curves first. The green curve is the current trajectory of greenhouse gases of carbon dioxide emissions projected into the future and corresponds roughly to case B, which Dr. Hansen was referring to before. The yellow curve represents an emissions trajectory based on an attempt to slow warming to this point, 2° Fahrenheit per decade that I discussed before that would give us a fighting chance. It actually might ultimately stabilize carbon dioxide concentrations in the atmosphere and climate change.

The difference between those two trajectories—what we are in for if we do business as usual and a trajectory that might stabilize the atmosphere—I'll call the greenhouse gap. That's the gap that has to be closed if we are to have a fighting chance. That represents about a 60 percent reduction of current carbon dioxide emissions and, unfortunately, perhaps an 80 percent reduction from future emissions in the year 2025, just 40 years hence because emissions are projected to grow with business as usual.

As I said, given this projected doubling in emissions over the next 40 years if we do nothing, we have a daunting task ahead. It is a task we must begin today.

Thank you.

[The prepared statement of Dr. Oppenheimer follows:]

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Testimony of Dr. Michael Oppenheimer

before the

Committee on Energy and Natural Resources

United States Senate

23 June 1988

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My name is Dr. Michael Oppenheimer. I am an atmospheric physicist and senior scientist with the Environmental Defense Fund, a private, non-profit organization. I would like to thank the Committee for giving me the opportunity to testify about the recent report, DEVELOPING POLICIES FOR RESPONDING TO CLIMATIC CHANGE, (referred to hereafter as the "Bellagio Report"), published by the World Meteorological Organization and the United Nations Environment Programme. The Environmental Defense Fund, along with the Beijer Institute of the Royal Swedish Academy and the Woods Hole Research Center, was an originator of the project which produced this report. I served on the steering committee for the two international conferences which provided the basis for the report, and I also contributed to its preparation.

This project was developed in the wake of publication of the report of the 1985 UNEP/WMO/ICSU Villach meeting in which experts on climate from around the world produced a concensus that global warming due to the emissions of greenhouse gases was indeed underway. An examination of policy options was recommended. The Bellagio Report, based on deliberations by two meetings involving scientists and policy-makers (called the Villach 1987 and Bellagio workshops), finds that the time for action in response to impending warming is NOW. In particular, the report recommends several steps to be undertaken immediately with the goal of slowing global warming. Other measures to cushion the consequences of unavoidable change, and to develop a coordinated international response, are also recommended, including consideration of an international convention or "law of the atmosphere".

In my personal opinion, greenhouse warming presents the most important global challenge of the next few decades, on a par with defense, disarmament, and economic issues. With warming apparently now measurable, we are already playing catchup ball. The Midwest drought is a warning: whether or not it is related to global changes, it provides a small taste of the dislocations society will face with increasing frequency if we fail to act. If measures are not undertaken soon to limit the warming, humans face an increasingly difficult future while natural ecosystems may have no future at all.

To illustrate the magnitude of the problem, let me briefly describe the causes of greenhouse warming. Certain gases which occur in the atmosphere in small amounts are growing rapidly in concentration due to human activities related to industry and agriculture. Primary among these is carbon dioxide, a product of coal, oil, and natural gas combustion. These "greenhouse gases" trap heat radiating from the surface of the earth which would normally escape into space, resulting in a warming of the surface. This increase in global temperature causes a concommitant rise in global sea level as ocean water expands and land ice melts. As long as the amounts of greenhouse gases increase in the atmosphere, this process will continue unabated.

There will be no winners in this situation, only a globe full of losers. Today's beneficiaries of change will be tomorrow's victims as the changing climate rolls past them like a wave that first sweeps you up, then drops you in the trough behind it. The very concept of conservation does not exist in a world which may change so fast that ecosystems, which are slow to adjust, will wither and die.

The technical findings of the Villach-Bellagio workshops include:

. Global mean temperature will likely rise at about 0.6 degrees Fahrenheit per decade and sea level at about 2.5 inches per decade over the next century. These rates are 3 to 6 times recent historical rates. By early in the next century the world could be warmer than at any time in human experience. Furthermore, there is no known natural limit to the warming short of catastrophic change, for as long as greenhouse gas growth continues in the atmosphere. At some point, these emissions MUST be limited.

. Because the oceans are slow to heat, there is a lag between emissions and full manifestation of corresponding warming -- a lag of perhaps 40 years. The world is now 1 degree F warmer than a century ago and may become another one or more degrees warmer EVEN IF EMISSIONS ARE ENDED TODAY. These changes are effectively irreversible because greenhouse gases are long lived. WE CAN'T GO BACK IF WE DON'T LIKE THE NEW CLIMATE. So action to slow the warming must be taken before full consequences are manifest.

. This committed warming means some adaptation measures, such as sea defense and coastal abandonment, are inevitable. But effective adaptation will be costly and for many nations, such as Bangladesh, infeasible.

. The natural environment cannot adapt effectively to such rapid changes. The impending warming must be viewed as A DISASTER FOR NATURAL ECOSYSTEMS. The mountaintop declines of red spruce in the eastern United States, generally ascribed to air pollution or climate variability, pale in comparison to the scope of change impending if warming continues. For instance, one model predicts biomass crashes in southeast pine forests in the next century if warming continues, with declines of up to 40% occuring over decadal periods. The recent dispute over oil exploration in the Arctic National Wildlife Refuge may be beside the point if the Arctic ecosystem is driven off the north coast of Alaska by climatic change.

. If climate changes rapidly, agriculture and water resources will be stressed. Even if global food supplies are maintained, one need only look to the current Great Plains drought to see the human and economic cost associated with hot and dry weather in the grain belt, weather of the sort which we can expect with increasing frequency in the future.

. Although some change is inevitable, and in fact appears to be already underway, unacceptable warming is not inevitable if action is begun NOW. Every decade of delay in implementation of greenhouse gas abatement policies ultimately adds about a degree F of warming; and no policy can be fully implemented immediately in any event. Limitation of warming to historical rates (about 0.2 degree F/decade) for some finite time would give societies and natural ecosystems a fighting chance at adjustment. But unlimited warming at any rate is ultimately problematic.

. The foregoing picture is the good news. The bad news is that climate change may not occur smoothly; rather it could occur in jumps which would render fruitless any attempts at planned adaptation. The advent of the ozone hole should make us cautious in assuming that atmospheric change will be gradual.

. Slowing warming to an acceptable rate and ultimately stabilizing the atmosphere would require reductions in fossil fuel emissions by 60% from current levels, along with similar reductions in emissions of other greenhouse gases. Given the projected doubling in emissions over the next 40 years (see Figure 1) in "business-as-usual" scenarios, we have a daunting task ahead.

Certain immediate policy responses can set us along the path toward climate stability. Measures recommended for immediate implementation include:

. Ratification, implementation and consideration of strengthening of the Montreal Protocol on CFC emissions.

. Development of national energy policies which encourage efficiency in generation, transmission and use.

. Investments in research and development of non-fossil fuel alternative energy systems.

. Encouragement of use of low-CO_2 fuels such as natural gas as a bridging measure.

. Control of nitrous oxide, methane and tropospheric ozone emissions where technology is currently available (such as tapping solid waste landfills for methane). Funding research and development on control methods where uncertainties remain.

. Reversal of the current deforestation trend since forests serve to store carbon which would otherwise aggravate the geenhouse problem.

. Consideration of a global convention on greenhouse gases.

. Planning for coastal protection and abandonment.

. Research support for global change basic science initiatives.

. Policy research on "how to get the job done".

The United States government should take the lead now with a series of measures in each of these areas. We still have a window of opportunity to limit these changes to acceptable levels. The development of these policies, their implementation, and the diffusion of these solutions to the rest of the world, should largely define the framework for scientific and technological development over the next few decades. Thus the problem of global warming presents both challenges and opportunities. But the pur uit of solutions and their implementation must begin today.

FUTURE CARBON DIOXIDE EMISSIONS *

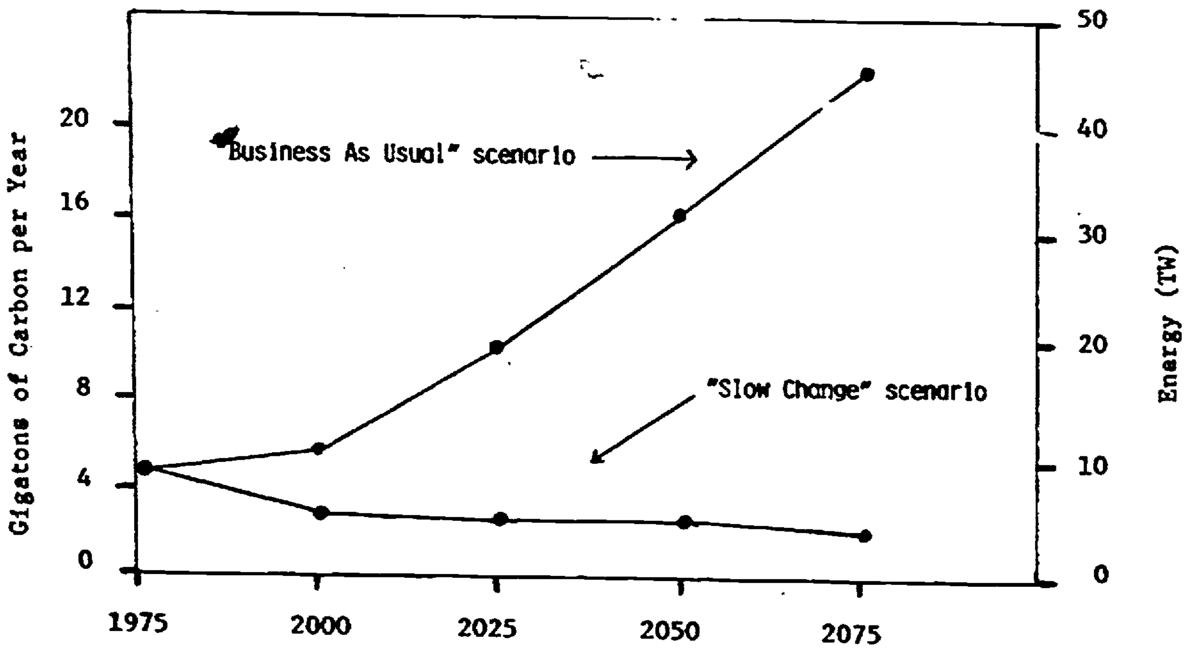

Figure 1

* Adapted from DEVELOPING POLICIES FOR RESPONDING TO CLIMATIC CHANGE, World Meteorological Organization and United Nations Environment Programme, 1988; WORLD COMMISSION ON ENVIRONMENT & DEVELOPMENT, OUR COMMON FUTURE, U.N.E.P., 1987; and I.M. Mintzer, A MATTER OF DEGREES: THE POTENTIAL FOR CONTROLLING THE GREENHOUSE EFFECT, World Resources Institute, 1987.

Senator WIRTH. Thank you very much, Dr. Oppenheimer.
Dr. Woodwell?

STATEMENT OF DR. GEORGE M. WOODWELL, DIRECTOR, WOODS HOLE RESEARCH CENTER

Dr. WOODWELL. Thank you. I am George M. Woodwell, Director of the Woods Hole Research Center. I wish to add strength to the assertions of the two previous speakers who have articulated things so splendidly and accurately.

We are embarked on a period of drastic climate change. We have lived through and developed our civilization in a period of substantial stability of climate. We are now entering a period when climates globally will change substantially.

The rate of change is of particular importance. The average changes in temperature of the earth that you heard described just a few moments ago are, of course, made up of extremes. The changes in the tropics will be very little. The changes in high latitudes will be substantial perhaps two and a half times, maybe two times, the amount of change described as the average change in the temperature of the earth or whatever amount of infrared absorptive gas accumulates in the atmosphere.

The amount that is usually settled on is the equivalent of the doubling of the carbon dioxide content. We expect that that would occur sometime early in the next century, certainly before the middle of the next century, 2030 or so. At that time the temperatures in the middle and high latitudes may be two times or so above the means we have heard discussed. We expect the means to run for the earth as a whole somewhere between 1 and a half and 5 and a half degrees Centigrade. So, we could have over the next decades changes in the temperature in the middle and high latitudes where we live and farther north, considerably farther north, that might approach a half a degree Centigrade to well over a degree Centigrade per decade. Those are very big changes measured in any calculus.

They are much larger than the capacity of forests, say, to adapt to climatic change. Forests are easily destroyed and not very easily rebuilt. A temperature change of the order of 1 degree Centigrade is the equivalent of moving northward under present climatic regimes roughly 100 to 150 kilometers. That would be 60 to 100 miles. That sort of change in a decade in the high latitudes is entirely conceivable as something that can occur in the next decades. That change has the potential for destroying forests over large areas at a high rate.

Now, why is that important? Well, it's important for several reasons, not the least of which is that we use forests very heavily, but also because forests contain a large amount of carbon. It is contained in the plants of the forest and in the soils. There is in the middle and high latitudes at least as much carbon stored in forests and their soils as there is in the atmosphere at the moment. Warming the earth at rates approximating those described and anticipated for the next years has the potential for speeding the release of that carbon by stimulating the decay of organic matter in soils much in excess of any potential for those forests for taking carbon out of the atmosphere and putting it back into soils and the bodies of plants.

That's a positive feedback system that has not been worked into the calculus. It's the kind of surprise that we can anticipate, the kind of surprise we have already observed in the ozone hole and in other aspects of global change. It has the potential for making the problem substantially worse, a much more rapid change than we have expected.

Well, these problems are big problems. The climatic change problem is totally entwined in the energy problem, the challenge of energy policy, where we get our energy from and how we use it and how efficiently we use it.

It is also tied up in the population problem. We forget that in 1950 there were just about half as many people around as there right now, and we have the potential for producing twice as many by 2030 or thereabouts. There are 5 billion people in the world at the moment. We use probably more than half of all the energy that is fixed by green plants globally in support of those 5 billion people. What will we do with 10 billion? We have the potential, as Dr. Oppenheimer just pointed out, of changing climatic zones, altering the productivity of agriculture and changing the potential of the earth for fixing carbon in green plants and changing it drastically.

If we can address these problems successfully—and I believe that we can—we have the potential for a very comfortable and promising future for the ~~human~~ enterprise. The problems unaddressed have the potential for turning the world into a form of chaos not greatly different from that produced by global war.

Let me show two graphs briefly to emphasize aspects of this problem that seem particularly important. This graph shows what is probably the most famous set of geophysical data ever produced. On the left margin of the graph is the concentration of carbon dioxide in the atmosphere. The abscissa, the lower margin that runs across the bottom, starts in 1958 and runs through the 1980's. The line shows the concentration of CO_2 over that period. The data were started by Dr. David Keeling of the Scripps Institution of Oceanography.

You can see and appreciate the upward trend in the data. That particular graph goes from about 315 parts per million on the left to about 350 which is where we are right now. The upward trend is caused by the net accumulation of carbon dioxide in the atmosphere, carbon dioxide produced by burning fossil fuels and by destroying forests.

Now, there is probably a third component in that accumulation caused by the warming itself, and that's this further component due to the decay of organic matter in soils. If the warming proceeds rapidly enough to destroy forests, that component can expand considerably.

The second point I would make here is the oscillation. The peaks all occur at the end of the northern hemisphere winter. These data were taken in the northern hemisphere at Maunaloa in the Hawaiian Islands. The minima, those lower numbers, occur in each year at the end of the northern hemisphere summer. We wondered for many years just why that occurred that way. We know now that

that's the metabolism of forests which carry on a net of photosynthesis above the decay that I mentioned, above the respiration, and that that is conspicuous during the summer. It pulls the carbon dioxide content down globally. It actually pulls the carbon dioxide content down by 100 billion tons, which is about a seventh of the total amount of carbon in the atmosphere each year, and it releases that back into the atmosphere annually through respiration leading to the peaks you see.

Well, a small change in the ratio of photosynthesis to respiration, the two fundamental physiological processes that determine heavily the balance of gases in the atmosphere, has the potential for changing the carbon dioxide content of the atmosphere. I make this point simply to hammer home the scale of the influence of living systems on the human habitat and the scale of the influence of forests in particular on the composition of the atmosphere and therefore this climatic problem. There isn't a solution to the climatic change problem that does not consider the forests of the earth and other biotic systems.

If we could look at the second viewgraph which shows the same sort of data over a longer period of time—we are starting now way back in 1740 and running through the 1980s—we see that upward trending curve is a characteristically exponential curve, the same kind of curve that population growth follows. It's a compound interest curve, a curve generated by a process that feeds on itself. Many, perhaps most, of the curves describing processes in nature follow such trends.

That curve is being produced at the moment. That upward trend is being produced at the moment by a net accumulation in the atmosphere of 3 billion tons of carbon in excess of the amount that is absorbed into the oceans and any other systems that absorb carbon including forests and other biotic systems. So, the net imbalance right now is 3 billion tons. We release through burning fossil fuels about 5.6 billion tons. There is a further release destruction of forests in the range of 1 to 3 billion tons of carbon.

If there are other releases, we are not able to measure them. There is probably a release due to the warming itself. We don't know what that is, but it doesn't matter. We do know that the imbalance is 3 billion tons right now.

If we could magically reduce the emissions by 3 billion tons, we could instantaneously stabilize the composition of the atmosphere. It would be a temporary stabilization, very temporary probably, but nonetheless that is the scale of the challenge. It is well within reach. We can do something about it.

What has to be done? There isn't any question, no question in the eyes of the group that met in the Villach and Bellagio meetings that Dr. Oppenheimer reported on, no question in the eyes of others who think about this problem. We must reduce the use of fossil fuels on a global basis, a reduction of the order of 50 to 60 percent is probably appropriate, and the sooner the better.

It is also true that cessation of deforestation on a global basis is completely appropriate to solve the climatic change problem and for many other reasons.

It is possible to store carbon in forests by rebuilding forests, by reforesting areas around the world. The rate of storage is about 1

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billion tons for roughly 2 million square kilometers of forests. So, if we can start forests going over 2 million square kilometers, a very large area, that area will continue to store carbon at the rate of approximately a billion tons a year for 40 or 50 years as that forest grows toward maturity.

Those three steps are clear and immediate. If we were looking for a single, simple signal policy that would lead the world—and we must lead the world. We, the United States, are the global leaders. We have greater potential in that realm than any other nation, greater flexibility to take that sort of initiative—that step would be to establish a policy immediately of reducing our emissions of fossil fuels by 50 percent over the course of the next years, perhaps a decade or so. That objective is totally consistent with continued economic welfare. It is totally consistent with other objectives in preserving environmental quality. It is totally consistent with economic strength——

Senator MURKOWSKI. Are you prepared to recommend how, Doctor?

Dr. WOODWELL. How would we do that? Simply through conservation, through changing standards, for instance, of efficiency for automobiles, by super-insulating houses, by building houses that don't require as much energy. And there are many, many ways of doing that.

So, I'm not at all doubtful that such an objective is realistic. If we could establish that as a signal step in the process of reducing reliance on fossil fuel globally, I would think that we would have done one of the strongest and wisest things possible.

Thank you.

[The prepared statement of Dr. Woodwell follows:]

TESTIMONY OF G.M. WOODWELL
BEFORE THE SENATE COMMITTEE ON ENERGY AND NATURAL RESOURCES,
WASHINGTON, D.C.
THURSDAY, JUNE 23, 1988

Rapid Global Warming: Worse with Neglect

I. Introduction: The Villach-Bellagio Report

I am a scientist, Director of the Woods Hole Research Center in Woods Hole, Massachusetts. I am also a member of the Board of Trustees of the Natural Resources Defense Council, a conservation law group with more than 75,000 members around the country. I appear before you in both capacities. My colleagues and I in science have done research on various aspects of climatic change for more than 25 years; my colleagues and I in the NRDC have made formal efforts spanning nearly two decades to make better connections in public affairs between what we know and what we do.

I am reporting on experience gained through two conferences held during the fall of 1987 in Europe dealing with climatic change. The first was in Villach, Austria, and was a review by scientists of the details of the global climatic warming that appears to be underway. The second, held in Bellagio, Italy, was an exploration of the implications of the changes in climate for governmental policies. A report of these conferences has been published by the World Meteorological Organization (WMO 1988) and is available to you. I am emphasizing in what follows the biotic interactions involved in climatic change because those interactions affect people most directly and have the potential for affecting the course of the climatic changes. I am also giving emphasis to the need for general solutions to the regional and global problems that will become increasingly acute through the next years. I find it necessary to do so because we tend to overlook the fact that 5 billion people now occupy the globe, twice the number present as recently as 1950. Before 2030 the human population could be 10 billion. The 5 billion we now have use half or more of the energy available from plants globally. Big changes in the human condition will be occurring without climatic changes. The climatic changes will compound the difficulties in accommodating such extraordinary rates of growth.

II. A Consensus among Scientists

Several points about climatic change now constitute a consensus held by meteorologists and other scientists who have worked on the problem. Most of these points have been made in slightly different form in the Villach-Bellagio report.

1. The dominant influence on global climate for the indefinite future is expected to be a continuous warming caused by the accumulation in the atmosphere of infra-red absorptive gasses, especially carbon dioxide and methane, but including nitrous oxide and the CFC's.

2. The warming marks the transition from a period of stable climates to climatic instability. Stable or very slowly changing climates have prevailed during the development of civilization. We are now entering a period of continuous warming accompanied by changes in precipitation. The changes in climate are predictable in general at continental and broad regional levels; they are not predictable locally.

3. The rate of the warming is uncertain. Estimates based on models suggest that a doubling of the carbon dioxide content of the atmosphere (or the equivalent through increases in other gasses) above the levels present during the middle of the last century will produce a global average warming of 1.5-5.5 degrees C. Such an effect is expected by the period 2030-2050.

4. The earth has warmed between 0.5 and 0.7 degree C over the past century and the rate appears to be accelerating.

5. The warming in the tropics will be less than the mean for the earth as a whole; in the middle and high latitudes the warming will exceed the mean by two fold or more and will fall in the range of 0.5-1.5 degrees C/decade.

6. The current sources of carbon dioxide are the combustion of fossil fuels and deforestation. The dominant source of methane is anaerobic decay.

7. A rate of warming in the middle and high latitudes that approaches 1 degree C/decade exceeds the rate at which forests can migrate and will result in the destruction of forests at their warmer and drier margin without compensating changes elsewhere. Such destruction of forests and soils release additional carbon into the atmosphere as carbon dioxide.

8. It is possible that the warming already experienced is stimulating the decay of organic matter in soils globally, increasing the total releases of carbon dioxide and methane.

9. No stimulation of the storage of carbon in forests or soils that is large enough to compensate for such rapid releases is known.

10. The warming will cause accelerated melting of glacial ice and an expansion of the water in the oceans. The effect will be an increase in sea level of 30 cm to 1.5m over the next 50-100 years.

11. The changes in climate anticipated over the next decades extend beyond the limits of experience and beyond the limits of accurate prediction. Surprises such as the discovery of the polar ozone holes are common in such circumstances. The possibility exists that a rapid warming will change the patterns of circulation of the oceans and produce sudden but profound changes in climate in regions such as western Europe, now kept warm by the Gulf Stream. The same changes may have equally surprising effects on the storage or release of carbon from forests and soils.

The warming will move climatic zones generally poleward, shift the arable zones of the earth continuously, cause large and continuous dislocations of natural vegetation, and cause flooding of low-lying areas globally. The arid zones of the northern hemisphere will expand because there is more land at higher latitudes in the northern hemisphere. The warming will be greatest in winter and will be accompanied by increased precipitation in high latitudes.

A one degree C change in temperature is equivalent to a change in latitude of 100-150 km, 60-100 mi. Rates of warming, if they occur as anticipated over the next decades, will exceed the capacity of forests to migrate or otherwise adapt. In that circumstance forest trees and other plants will die at their warmer and drier limits of distribution more rapidly than forests can be regenerated in regions where climates become favorable. The destruction of forests will add further to the releases of carbon to the atmosphere. The seriousness of this problem will depend heavily on the rate of warming. There is sufficient carbon in forests and soils of middle and high latitudes to affect the atmosphere significantly. While there is no proof of this process and there will probably not be proof until the changes are well underway, the process will hinge heavily on rates of warming. Rates that approach 1 degree per decade exceed by a factor of 10 or more the capacity of forests to accommodate the changes.

III. What Can be Done?

The earth will warm as a result of the changes in the composition of the atmosphere that have already occurred. But an open-ended, continuous warming that speeds the rise in sea level and destroys forests over large areas is so thoroughly disruptive of the human enterprise as to preclude any thought that civilization might "muddle through". Can the warming be checked?

The annual increase in the atmospheric burden of carbon dioxide alone is about 3 billion tons currently. The global warming has the potential for increasing this net accumulation by speeding the release of carbon from forests and soils without causing an equivalent increase in the rate of storage. No estimate is available of the extent to which this additional source of carbon dioxide is likely to compound the problem. But the new source will diminish as the warming diminishes. At least three possibilities exist for reducing or eliminating the imbalance and moving toward long-term stability of climate:

1. a reduction in the use of fossil fuels globally, now estimated as the source of about 5.6 G-tons of carbon annually;

2. a reduction in or cessation of deforestation, now estimated as releasing 1-3 G-tons annually;

3. a vigorous program of reforestation that would remove from the atmosphere into storage in plants and soils about 1 G-ton of carbon annually for each $2x10^6$ km^2 tract in permanent forest.

Further adjustments in emissions will be appropriate as experience accumulates. Such steps are appropriate now and possible. They will bring widespread ancillary benefits to the human enterprise. Further delay increases the accumulation of greenhouse gasses in the atmosphere, the severity of the warming that must be accommodated, and the risk of unexpected consequences that lie beyond the limits of current prediction.

These changes are possible now. They will require adjustments in the efficiency of use of energy in the industrialized nations and imaginative and far-reaching changes in the patterns of development of the less industrialized nations. Recognition of the need for the transition to a new era in the management of the earth's resources opens new opportunities for industry and governments to pursue new paths for sustainable economic development on a global basis.

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Senator WIRTH. Thank you very much, Dr. Woodwell.

We have been joined by Senator Chafee who is advertised as our first witness this afternoon, and I had promised Senator Chafee that as soon as he arrived—I know he has been involved in this for a long time. We are delighted to have you with us, John, and if you have any kind of opening remarks or statement that you might like to make, please do so.

STATEMENT OF HON. JOHN H. CHAFEE, U.S. SENATOR FROM RHODE ISLAND

Senator CHAFEE. Well, thank you very much, Mr. Chairman. And I want to commend you for holding these hearings, and certainly you have got a list of excellent witnesses. I apologize for not being here when I was meant to be. It is one of those days that we all have where we are meant to be several places at once. But certainly there is no better time to hold these hearings than right now.

Destruction of the earth's climate system through the burning of fossil fuel, as was just mentioned, and the release of manufactured chemicals which I am sure will be touched on later, has been treated as a distant threat or some kind of theoretical problem. But I think people are beginning to wake up to this. You can look at Ocean City, Maryland and see the sea levels are already rising. The drought which we are enduring, particularly in the midwest and in the central part of the country, typifies the kind of changes in rain patterns that are predicted to occur as a result of the greenhouse effect.

If there is one point I could make, Mr. Chairman, it is this. There are a great many questions about the greenhouse effect that can't be answered today. But I don't think we ought to let scientific uncertainty paralyze us from doing anything. It is always convenient to find an excuse not to do something, and there's always an excuse out there not to do something. But I think the issue before us is what steps should we be taking today to help solve the problem in addition to doing more scientific research.

On March 31 of this year, 41 Senators joined me in a letter to the President urging him to call upon all nations of the world to begin the negotiations of a convention to protect our global climate. And that proposal is under review, but the upbeat sign is we are seeing progress on the international level. This matter of the global climate change was discussed at both of the two meetings between the President and Secretary Gorbachev here in Washington and in Moscow. The UNEP, the United Nations Environmental Programs, and the World Meteorological Organization are establishing an intergovernmental panel to work on this.

I noticed Senator Baucus here who has been so active on this in the Environment Committee and who spoke earlier. He and I have worked together on this. I remember chairing the first hearings I think in June of 1986 on this matter.

I want to congratulate you and urge you onward. With everybody paying attention to this, I'm glad it's getting a high level of visibility. Certainly it has a good turnout. I hope we can continue this struggle because it is up to us to do something. As was pointed out by Dr. Woodwell, the U.S. is the leader, and we have got to take the lead on these matters.

Thank you, Mr. Chairman.

[The prepared statement of Senator Chaffe follows:]

STATEMENT OF SENATOR JOHN H. CHAFEE
BEFORE THE SENATE COMMITTEE ON ENERGY AND NATURAL RESOURCES
HEARING ON GLOBAL CLIMATE CHANGE
JUNE 23, 1988

Mr. Chairman. You have selected one of the world's most important and difficult environmental problems as the topic of this hearing. I want to congratulate you for your efforts and for your wisdom. What better time to hold a hearing on global warming than during a 100 degree plus heat wave and a world-wide drought?

Many jokes can be made about the timing of this hearing and the current problems with excessive heat and lack of rain but this is no laughing matter. So far, destruction of the earth's climate system through the burning of fossil fuels and the release of manufactured chemicals has been treated as a distant threat or as a theoretical problem.

Finally, people are waking up to the fact that the problem is real and, whether we like it or not, we are going to have to deal with it. We are going to have to deal with it soon!

We can look at Ocean City, Maryland and see that sea levels are already rising. The drought typifies the kind of changes in rain patterns that are predicted to occur as a result of the greenhouse effect. The heat obviously gives us a preview of what can be expected if we continue to stick our head in the sand and deny that we have a problem.

Mr. Chairman. Clearly, there are a great many questions about the greenhouse effect that cannot be answered today. But we should not let scientific uncertainty paralyze us. The issue for us is "what steps should we be taking today to help solve this problem in addition to more scientific research?"

On March 31 of this year, 41 Senators joined me in a letter to President Reagan urging him to call upon all nations of the world to begin the negotiation of a convention to protect our global climate. That proposal is still under review and, in the meantime, we are seeing progress at the international level.

At our urging, the problem of global climate change was discussed by the world's leaders at the two Reagan-Gorbachev summits, here in Washington and again in Moscow, as well as at the economic summit recently held in Toronto. At the same time, the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) are establishing an intergovernmental panel to work on the matter.

We are making progress but we have a long way to go and can be doing a better job here at home. The way we waste energy in this country is a crime. There are numerous things we can do that would not only help solve the greenhouse problem but would make economic sense as well. Improved energy conservation and a requirement that autos run more efficiently would be two good items to consider.

In the Environment Committee, I chaired a series of hearings on this problem in June 1986. We have come a long way since then and, with the help of you and your Committee, the press, dedicated scientists, and a host of interested professionals, we are managing to capture the attention of people all over the world. That kind of grassroots support is critical if we are going to succeed in our battle.

Mr. Chairman. Again, I commend you for your interest and commitment to working on this matter and I look forward to working with you as we go forward.

Senator WIRTH. Thank you very much, Senator Chafee. You have certainly been very active in the lead in so many aspects of this issue.

Let me ask Senator Murkowski, who has joined us, if he has any kind of a statement or comments that he might like to make.

STATEMENT OF HON. FRANK H. MURKOWSKI, U.S. SENATOR FROM ALASKA

Senator MURKOWSKI. Well, thank you very much, Mr. Chairman.

First of all, I am fascinated, as we all are, by the significance of the information. And I think particularly Dr. Woodwell's presentation certainly stimulated my thought process to how we're going to do this, and his response to my question that by instituting CAFE standards and insulation in homes and so forth could make a substantial reduction in the hydrocarbons. But indeed, Doctor, when you were talking about a 50 or 60 percent reduction, it is inconceivable to me that you can achieve that kind of reduction from those limited capabilities in those narrow areas.

And I am just wondering if, indeed, we're not looking at some more significant alternatives such as realistically increasing a dependence on nuclear power generation which is something that our country has got a phobia over for reasons that we don't have to go into. But considering and being practical, we only have so many alternatives. And I'm just wondering if realistically the scientific community is prepared to address whether one of those alternatives has to be nuclear or whether we can achieve your percentage reduction some other way.

And I think there was a reference to my State of Alaska with regard to the question of the Arctic ecosystem changing. And I look at these projections here, and it's really alarming. I noticed the red has moved up to our area where it is still nice and cool. But there is no question about it. Things are getting warmer. The winters are becoming more mild.

So, my question is a general one. Is it, indeed, a reality that we must look more aggressively to nuclear as a release because I don't see the public demanding any reduction in the power requirements that our air conditioners run off of, everything else that we enjoy.

Senator WIRTH. Senator Murkowski, if we might hold the specific questions till we finish the three witnesses, if we might, because I know there are policy pieces that will be reflected in each of the statements of the three people here.

Senator MURKOWSKI. I'm going to have to excuse myself. So, I would appreciate it if one of my colleagues would be sure and see that perhaps one of the witnesses could respond.

Senator FORD. You can depend on it.

Senator WIRTH. Frank, this will be the first of a number of hearings that we are going to be having on where we go from here. And certainly alternatives to fossil fuels are going to be one of the major focuses of this committee's concerns.

We have three remaining members of the panel: Dr. Suki Manabe, who has been with us before. We are really delighted to have you back. Dr. Manabe, as I understand it, is going to focus particularly on soil precipitation. We will then move to Dr. Dan

Dudek from EDF who is going to talk particularly about the agricultural implications of the issues being discussed this afternoon. And finally, we will end up with Dr. William Moomaw who is going to bring us back to some broad policy concerns once more.

So, Suki, thank you very much for being here. And once more, we look forward to having your testimony.

STATEMENT OF DR. SYUKURO MANABE, GEOPHYSICAL FLUID DYNAMICS LABORATORY, NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Dr. MANABE. Mr. Chairman and members of the committee, I appreciate the opportunity to appear before you today. As I did before this committee last November, I would like to discuss the large-scale change in soil wetness. These changes which may have profound practical implications have received attention at various research institutions in North America and Europe. I shall begin my discussion by referring to the results obtained from the mathematical model of climate developed at the Geophysical Fluid Dynamics Laboratory of NOAA.

Now, the first viewgraph shows the change in soil wetness in response the doubling of greenhouse gases in the atmosphere. And this is a model-produced result. This figure indicates that in the summer soil dryness is reduced over very extensive mid-cost required regions over the North the and Eurasian continents. The yellow indicates a region of a modest reduction, and the pink indicates a region where the reduction is relatively large.

In high latitudes, this midcontinental drying in summer is mainly due to the change in the seasonable variation of snow patterns. As you know, in winter, of course, snow prevails over the major part of the high latitude part of the continent until it melts in the spring. The snow reflects a large fraction of solar radiations so that when snow disappears, a larger fraction of insulation is absorbed by the ground which makes more energy available for evaporation, so that when the snow melting season ends, then the rapid drying of the soil begins from spring to summer.

Now, in the very warm climate spring to summer begins earlier as the snow melting season ends earlier. Therefore, the soil wetness in summer is reduced. This is one of the important mechanisms in higher latitude drying.

In the middle latitude a similar mechanism involving snow cover occurs particularly in high elevation regions. However, in middle latitudes there is another factor which is more important. That is a change in the precipitation in the middle latitude rain belt. This is illustrated by a schematic diagram. That blue line in the diagram indicates how the middle latitude rain belt moves with respect to season. In the abscissa you will see the different months of the year starting from January and ending December. And this rain belt is at the southern most latitude in winter. And as you go towards summer, it moves northward although the summer rain belt becomes a little more obscure by the convective rain which goes around. And in Autumn it starts to shift southward again.

Now, in the CO_2 rich or greenhouse gas rich case, the atmosphere is warmer and air can contain more moisture. So, the warm, moisture-rich air can penetrate into higher latitudes, thereby bringing more precipitation over there. Thus, in the northern half of the rain belt, you get much more rainfall in the greenhouse gas rich case. In the southern half, it does not. And so what happens in the warmer climate the ground surface is warmer and pollution not longer almost such everywhere. On the other hand, the precipitation increases much more in the northern half of the rain belt, but not in the southern half. Let's assume that you happen to live in a middle latitude location as season proceeds from January to April, you gradually get into the southern half of the rain belt where it is drier. This is another mechanism which gives you drier summer soil in the mid-continental region in the middle latitudes.

As soil gets drier, the relative humidity and cloudiness in the lower atmosphere, thus very dry. Thus more sunshine hits the ground. Therefore, there is more energy available for evaporation, and the soil gets even drier. Clouds are reduced further and soil becomes. As the ground gets drier, and hotter, the lower atmosphere becomes hotter, thus over continental sector jet stream tends to move northward, thereby further reducing the precipitation in the mid-continental regions. These are the mechanisms of mid-continental summer drying as determined by a mathematical models of climate.

The summer reduction of soil wetness does not continue to winter. The model-produced discussed drought here is a rather seasonal phenomenon.

If you look at the next picture, the winter soil is mostly wetter in the warmer climiate. The rain belt is located at the farthest south in the winter so that you are in the northern half of the rain belt where the increase of precipitation makes the soil wetter. Other mechanisms are also involved in a warmer climate a larger fraction of precipitation falls as rain. Futhermore, accumulated snow tends to melt easier in warmer climate, thereby making the soil in winter wetter.

But one of the interesting things, which Jim Hansen mentioned earlier, is that soil wettness is reduced in the southwestern part of the United States in particular, in Southern California and its neighborhood where—you get most of rainfall in winter. As I noted earlier, the winter rain belt is located at the southern most latitude in winter. So, southern California is at the southern fringe of this rain belt where it has become drier in a warm climate so that you can see dry regions up here in the southwestern part of North America in winter. This is a result which appears in most of the modeling experiments, not only in our own, but also in many other results.

In short, these soil moisture changes substantially in the very crucial region of the United States. I have to emphasize, however, that modeling results about the soil wetness change are less robust than the temperature change which Jim Hansen discussed explained. It's important to note that the results obtained by various modeling groups are not in complete agreement though more recent results indicate mid-continental summer dryness. In my opinion, some uncertainty in the estimate of future hydrologic changes stems from summer dryness.

And I think this is due to our inability to make sufficient by realistic models which correctly incorporate, the various physical processes, in particular, the treatment of the land surface process is highly rudimentary at the present time. For example, the processes of the biosphere-climate interclim that Dr. Woodwell thinks are very important are not included in the model. So, it is very urgent to improve the climate models in order to gain more confidence in our predictims.

These results clearly indicate that summer reduction of mid-continental soil moisture results from global warming and is a very large scale phenomenon. The physical processes responsible for this enhanced dryness appear reasonable. In summary it is likely that severe mid-continental summer dryness will occur more frequently with increasing atmospheric temperatures as warming becomes larger and larger toward the next century.

One is tempted to ask whether the current dry condition in the United States results from the general warming trend in the northern hemisphere which Dr. Hansen mentioned earlier.

Unfortunately, I have not analyzed the current drought enough in sufficient detail to discuss this topic with confidence. However, since the past increase of global mean surface temperature during this century is only several tenths of a degree so far, natural variability of surface conditions can easily overshadow any surface reduction of soil moisture induced by this much warming. So, it is more likely that the current drought is a manifestation of the natural fluctuation of soil dryness rather than greenhouse-induced. However, I suspect that the process of dryness which I identified by our numerical experiment may be involved in aggravating current dry conditions. And I feel that this current drought provides an excellent example of the kind of drought which occurs more frequently as the global warming becomes larger.

In concluding my testimony, I believe it is essential that increased research efforts be devoted to improving the basic component of climate models in order to improve the reliability of our predictions. One common shortcoming of the current models is the coarseness of their computational resolution. This not only distorts the dynamics of a model atmosphere, but also prevents us from predicting geographical details of future climate change. When you try to ask what is a climate change in a State, e.g.) Colorado, we are helpless. The additional computer resources, including the supercomputer, are desired for this purpose.

Obviously, prediction of future climate change should be continuously verified and updated through continuous monitoring of the climate and the factors inducing climate change. In order to do this, a major commitment of resources are needed for satellite and in-site observation of our environment.

Mr. Chairman, this completes my present statement.

[The prepared statement of Dr. Manabe follows:]

STATEMENT OF

SYUKURO MANABE

GEOPHYSICAL FLUID DYNAMICS LABORATORY
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

BEFORE THE

COMMITTEE ON ENERGY AND NATURAL RESOURCES
UNITED STATES SENATE

JUNE 23, 1988

Mr. Chairman and Members of the Committee:

I appreciate the opportunity to appear before you today to comment on climate changes due to the future increase of greenhouse gases. As I did before this Committee last November, I would like to discuss the large-scale changes in soil wetness. These changes, which may have profound practical implications, have received increased attention at various research institutions in North America and Europe. I shall begin my discussion by referring to the recent results (1,2) obtained from the mathematical models of climate developed at NOAA's Geophysical Fluid Dynamics Laboratory.

The mathematical model of climate used for this study is a three-dimensional model of the atmosphere coupled with models of the land surface and a simple mixed layer ocean. It includes the effects of solar and terrestrial radiation and the hydrologic cycle and explicitly calculates the general circulation in the atmosphere using the hydrodynamical equations. It has been shown that this type of climate model successfully simulates the seasonal and geographical distribution of climate parameter. The impact of increased greenhouse gases on climate was evaluated by comparing climates of the model which have the normal and above-normal concentrations of atmospheric carbon dioxide.

A map of the CO_2-induced change of soil moisture for the June-July-August period is illustrated in Fig. 1a. This figure indicates that in summer, soil becomes drier over very extensive, mid-continental regions of North America, Southern Europe and Siberia in response to the doubling of atmospheric carbon dioxide. In some regions, the reduction amounts to a substantial fraction of the soil moisture present in the normal-CO_2 case.

Over Siberia and Canada, changes in snow cover are responsible for the CO_2-induced reduction in soil moisture. In these regions extensive snow cover prevails during winter before melting in the late spring. Since snow cover reflects a large fraction of incoming sunshine, its disappearance increases the absorption of solar energy by the land surface to be used as the latent heat for evaporation. Thus the end of the spring snowmelt season marks the beginning of the seasonal drying of the soil that takes place in summer. In the warmer high-CO_2 world, the snowmelt season ends earlier, bringing an earlier start of the spring to summer reduction of soil moisture. As a result, the soil becomes drier in summer.

Over the Great Plains of North America the earlier snowmelt season also contributes to the CO_2-induced reduction of soil wetness in summer. In addition, changes in the mid-latitude precipitation pattern also contribute to the reduction of soil wetness in summer over North America and Southern Europe. Both of these regions are under the influence of a rainbelt associated with the typical path taken by mid-latitude low pressure systems. In the high CO_2 atmosphere, warm moisture-rich air penetrates further north than in the normal-CO_2 atmosphere. Thus the precipitation rate increases significantly in the northern half of the mid-latitude rainbelt whereas it decreases in the southern half. Since the rainbelt moves northward from winter to summer, a mid-latitude location lies in the northern half of the rainbelt in winter and in its southern half in summer. At such a location the CO_2-induced change in precipitation rate becomes negative in early summer, contributing to a reduction of soil moisture. The summer dryness is enhanced further due to the increased sunshine reaching the ground as reduced evaporation from the drier continental surface causes a decrease in cloudiness.

The summer reduction of soil wetness discussed above does not continue through winter. In response to the increase of atmospheric carbon dioxide, soil wetness increases in winter over extensive mid-continental regions of middle and high latitudes (as indicated in Fig. 1b). In middle latitudes, this is mainly due to the increase of precipitation in the northern half of the middle latitude rainbelt. In high latitudes, a larger fraction of precipitation is realized as rainfall, making soil wetter. Fig. 1b also indicates that soil wetness is reduced in winter around Southern California and Mexico. The reduced rainfall in the southern half of the middle latitude rainbelt is again responsible for this enhanced dryness.

Upon inspecting Fig. 1, one should keep in mind that only these very broad scale features of the soil moisture changes are significant. For example, many of the small scale features in the tropics and Southern Hemisphere are not regarded with much confidence. This is partly because the climate models used in this study have coarse computational resolution and fail to simulate the small scale features of the hydrologic change. Furthermore, the detailed features of the CO_2-induced change are often obscured by large natural fluctuations of soil wetness, thereby making the identification of these features very difficult.

One should also note that the various research groups have not reached unanimous agreement (3,4) on the issue of the mid-continental summer dryness. Results from more recent studies (5,6) appear to agree better with those presented here (7,8). In my opinion, some uncertainty in the estimate of the future hydrologic change stems from the difficulty of reliably incorporating into a climate model various relevant physical processes, such as the land surface water budget and ocean-atmosphere interaction. Nevertheless, the above discussion clearly indicates that the summer reduction of mid-continental soil moisture results from the global warming and is a very large scale phenomenon. The physical process responsible for this enhanced dryness appears reasonable. In summary, it is likely that severe mid-continental summer dryness will occur more frequently with increasing atmospheric temperature.

One is tempted to ask whether the current dry condition in the United States results from the general warming trend in the Northern Hemisphere. Since the past increase of global mean surface air temperature during this century is about several tenths of a degree Celsius, natural variability of surface conditions can easily overshadow any summer reduction of soil moisture induced by the warming. Nevertheless, it is likely that the processes identified by our numerical experiments are involved in aggravating the current dry condition.

In concluding my testimony, I believe it is essential that increased research effort be devoted to improving the basic components of climate models in order to improve the reliability of our predictions. One common shortcoming of the current models is the coarseness of their computational resolution. This not only distorts the dynamics of a model atmosphere, but also prevents us from predicting the geographical details of future climate change. Improved computer support is required for better computational resolution.

Obviously the prediction of future climate change should be continuously verified and updated through continuous monitoring of the climate and the factors inducing climate change. In order to do this, increased observations of our environment are required.

Mr. Chairman, this completes my prepared statement. I would be glad to answer any questions you might have.

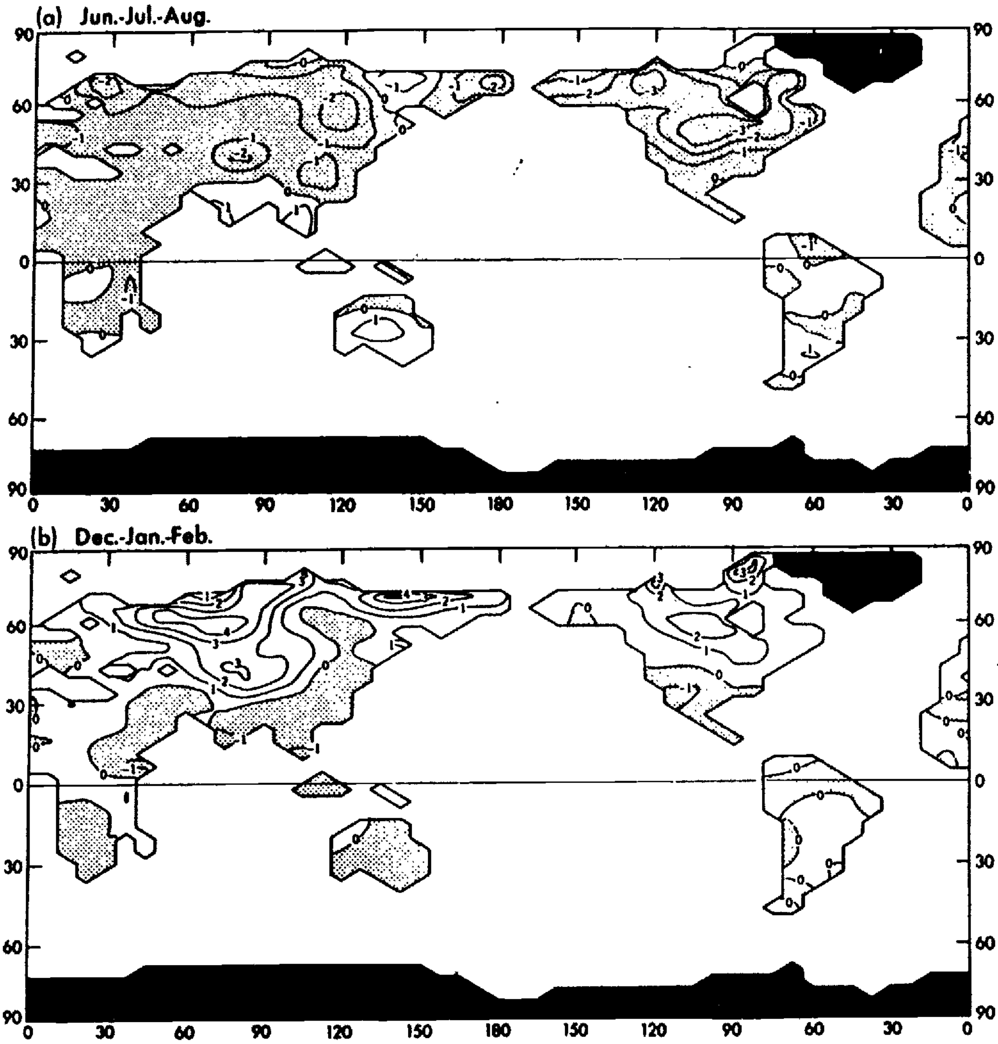

Fig. 1 The geographical distribution of the difference in soil moisture (cm) between the high CO_2- and the normal CO_2-experiments. See (2) for further details. (a) June-July-August period. (b) December-January-February period.

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Senator WIRTH. Thank you very much, Dr. Manabe.

Dr. Dan Dudek from the Environmental Defense Fund will focus in particular on the agricultural implications of global warming. Dr. Dudek, thank you for being here.

STATEMENT OF DR. DANIEL J. DUDEK, SENIOR ECONOMIST, ENVIRONMENTAL DEFENSE FUND

Dr. DUDEK. Thank you for inviting me, Mr. Chairman. My name is Dan Dudek. I'm a senior economist with the Environmental Defense Fund, but more importantly, I'm an agricultural economist both by training and avocation.

I don't think we need to be reminded by current headlines of the incredible sensitivity of agriculture to weather. It is the most weather-sensitive sector of our economy. At the same time, I'm not here to tell you that current drought conditions are, in fact, evidence of a global climate change. Rather, I think that the drought that we are currently suffering is an opportunity to help us conceive of what a greenhouse world would look like.

What I will present today in my testimony are results from analyses that we have conducted at EDF concerning what agriculture might look like under a changed climate. I would emphasize that these changed climatic conditions are normal conditions under a changed climate and not abnormal drought conditions as we are experiencing them now.

If I could have the first slide please. What we have done is to integrate both changes in atmosphere as manifested in terms of temperature and changes in evapotranspiration, water demand by plants with agronomic models which describe the relationship of crop productivity to temperature increases. Crop productivity is measured on the vertical access; temperature on the horizontal. As you can see, this is clearly a case where more is not better. In fact, for corn we have estimated for one particular climate scenario, that of the scenario A, corn yield reductions ranging between 22 and 27 percent depending upon both location and the treatment of carbon dioxide effects.

Other than temperature, there will be a whole host of additional stresses on crops in agriculture. These include traditional environmental pollutants, ozone and perhaps also increases in ultraviolet light associated with stratospheric ozone depletion. The soil moisture changes described by Dr. Manabe are important. These are not included in the model. Increases in concentration in carbon dioxide have a positive effect.

So, the results I will present today emphasize three different aspects of the problem. First is the carbon dioxide effect; second, that associate with climate change impacts; and third, the combination of these two. I will emphasize the latter two—that is, the climate change effects and the combination of the two—as being the most likely outcome.

If I could have the second slide please. In our work we integrated the biologic changes with an economic model, one developed by the U.S. Department of Agriculture and adapted for this purpose. It is a national model. And these results show aggregate production changes for the U.S. economy under a changed climate, in this case one associated with a doubling of the CO_2 concentration.

If we look at the two sets of bars—that is, those in the middle and those on the far right, one for climate change and one for combined—let's, for example, look at the yellow bar. That is that associated with corn. Current estimates are that the corn crop right now is suffering about an 11 percent decline in production. We are entering a critical period for corn in the next 10 days. We know the number of days above 95 degrees, as well as the amount of moisture available for corn, is a critical determinant of its yield. The range of yield reductions for corn predicted from our analysis are 9 to 14 percent.

For wheat, oats and barley, two other crops which have been mentioned as being significantly stressed currently in the drought situation in the middle west and great plains, we have predictions of changes in yield ranging between 1 and 20 percent. Current USDA estimates are for 22 percent national reduction in the production of those three commodities. So, again, we are in roughly a similar range of agreement.

If we step back and take a look at this question from an aggregate standpoint and ask what are the impacts in terms of the bottom line, dollars, the range of impacts here for both the combined and the net effects run between $1 billion and $12 billion on an average annual basis. Now, how can we stack that up against current conditions. Currently we are estimating that drought losses will run, as of right now, about $3 billion.

We can also get a rough magnitude of the size of these damages by comparing them with other environmental stresses on agriculture. It has been estimated that damages due to tropospheric ozone or smog are about $2 billion annually. Those associated with ultraviolet light and its increase from stratospheric ozone depletion are about $2 billion and a half annually. So, this is a very severe and drastic change indeed. I would emphasize that these are under normal conditions of a future climate.

Associated with the production declines, we would expect price increases reflecting reduced availability and scarcity of crops. We can also compare the predictions from these modeling studies with current events right now. For example, the purple bars show the response for soybeans, showing roughly about a 75 percent increase in price under the climate change only scenario. That compares with the jump in July soybean prices on the future markets of about 100 percent currently. If we look at July corn in the futures market, that's about a 72 percent increase. We're showing something around the order of a 65 percent increase, et cetera. We can continue to make these comparisons.

The point is here, first, that we have seen a rekindled interest in fear of inflation in the markets overall and a weakening of confidence in financial markets as a result.

The third slide please. One of the responses that we would expect to occur for climate change is a shifting cropping pattern, shift in location of crops in responding to the differential environmental stresses of climate change, as well as the availability of water resources. On this slide the yellow and red bars similarly show for climate change and for the net effect increases in dry land crop acreage that would be stimulated in the northwestern part of the United States associated with climate change. That is, one of the compensations for the yield reductions is to increase the intensity of agricultural development. In fact, one of the problems associated with such shifts and such increased acreage is whether resources, like soil moisture, as Dr. Manabe indicated, will be adequate to support that. Those changes have not been included in this analysis.

The next slide please. One of the other results that we observe is a shift in cropping methods—that is, from dry land systems to irrigated agriculture. This slide shows the associated changes in irrigation water demand. As you can see, in the northern tier states in particular increases of roughly 40 percent or more in terms of irrigation water demand are forecast.

The question again is whether supplies will be available. As we have precipitation changes, we will change the mix between rain and snowfall. In one study that has been done in California, for example, the result is an earlier spring snow melt. There is a greater runoff, but that runoff is not able to be captured by the existing dams. They were sized for normal historic climates and not for changed climates. In order to maintain their flood control capabilities, those releases have to be increased. The result is a reduction in the free water storage provided by the snowpack and a reduction in the deliveries of irrigation water supplies to state water project areas in particular in California. On an average annual basis, these run up to 30 percent; under adverse conditions, they could be as high as 50 percent.

A conservative estimate of the value of investments in California water supply works is roughly $15 billion to $20 billion. A question here is since water supply investments have been politically contentious—one recent example is the Two Forks Dam proposed in Colorado, one that has been called the dinosaur—we might ask legitimately whether, in fact, climate change will resurrect the dinosaurs.

In conclusion, the results that we are demonstrating here today are, in fact, robust across a wide range of model studies, some of which are being conducted by the Environmental Protection Agency now under the auspices of the Global Climate Protection Act. They lead to several recommendations.

First, perhaps what is most appropriate is the current advice being pandered on Wall Street; that is, we ought to diversify our portfolio. We ought to hedge against these kinds of risks. By that I mean we ought to expand the range of choices that we have available to us.

If we look to the success of achieving cooperative international agreement to manage the problem of stratospheric ozone depletion, in part that was facilitated by the existence of alternative chemicals that we could turn to. Those alternatives lessened the sharpness of the tradeoff between economic wellbeing and environmental quality. It is important that we develop those options now before crisis situations are upon us.

Next, productivity research and development is very important. One way to think about the kinds of productivity impacts in agriculture that we have been showing is to think about what kinds of increase in productivity would be required to compensate. Over the past several decades, we have averaged about a 1 and three-quarter percent per year increase in agricultural productivity. For some crops, it would take nearly two decades of that kind of sustained effort just to stay even with the kinds of yield reductions that we have been showing.

Efficiency has been mentioned both with respect to energy, in particular end use, and in generating energy. One of the important compensations that we predict is an expansion of groundwater use. Groundwater use is critically dependent upon energy pricing. It determines its feasibility and thus the ability of the use of that resource to compensate for these kinds of agricultural stresses.

Water efficiency is also important. And in that regard, one of the very important things that we can do is to give citizens in general the correct signals, give them the right incentives. This is true for both energy and for water. In the water area, we can develop water markets which would both facilitate the flexible movement of water in response to changes in crop location, as well as to give existing water users reasons to conserve water.

In particular in the energy arena, including environmental effects or environmental costs in energy investment decision making would be an important contribution to assuring that we make the correct choices about our energy future.

I thank you for the opportunity to address the committee today.

[The prepared statement of Dr. Dudek follows:]

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STATEMENT OF DR. DANIEL J. DUDEK
SENIOR ECONOMIST, ENVIRONMENTAL DEFENSE FUND

BEFORE THE

SENATE COMMITTEE ON ENERGY AND NATURAL RESOURCES

concerning

GLOBAL CLIMATE CHANGE

June 23, 1988

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Mr. Chairman and members of the committee, thank you for the opportunity to testify at this hearing concerning global climate change. The committee's interest in this problem at this time is a strong signal of the active concern and priority attached to this problem. One of the difficulties involved is conceiving the problem. We are fortunate that the science allows us to simulate, however uncertainly, possible alternative futures with computer models. As vivid as their pictures of the future might be, they fail to capture those changes in a human day-to-day context. The daily headlines concerning the high temperatures and drought currently scourging the mid western part of the nation help to complete the picture.

The buffeting that agricultural communities are suffering is a tangible reminder of our vulnerability to weather and the stakes involved in the threat of global climate change. My testimony today centers on a study undertaken by the Environmental Defense Fund, a copy of which will be submitted for the record, to describe the implications of climate change for U.S. agriculture and its customers. While the study examines only one possible future climate outcome representing normal weather, the results have broad similarity to current conditions. Crop prices would rise, production would fall, and competition for water would increase dramatically. Domestic consumers would pay higher prices and foreign importers would be fortunate to receive any crop.

As stewards of the future and managers of today's resources, we should ensure that the nation possesses a diversified portfolio of strategies to respond to these threats. Agreement in Montreal on protecting the ozone layer was possible because feasible, practical alternatives existed. We need investments and instituional changes that will broaden our alternatives, lessen the burden of response, and hedge against catastrophic surprise. Continuing with business as usual is a huge gamble that market forces or future policy-makers will have enough vision, time, or resources to produce cost-effective alternatives for responding to climate change.

ASSESSING THE IMPLICATIONS OF CLIMATE CHANGE FOR AGRICULTURE

General Approach

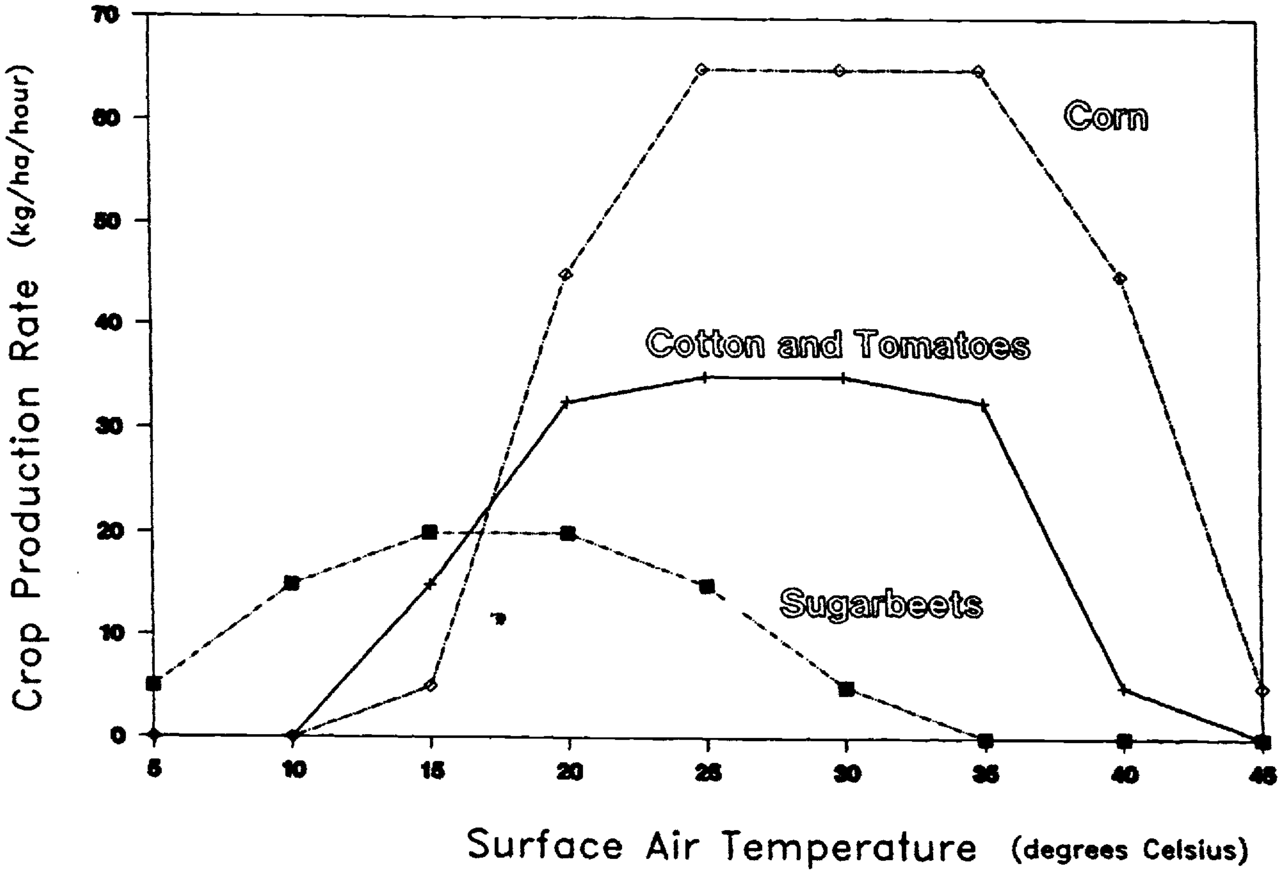
The basic approach in our study was to integrate basic physical, biological, and economic processes. Predictions of important climatic factors like temperature, precipitation, and evaporation are taken from general circulation models (GCMs) such as those developed at NASA's Goddard Institute of Space Studies (GISS) and the General Fluid Dynamics Laboratory (GFDL). Results from the GISS GCM were used in this study (Hansen, et al., 1986). Crop growth depends critically upon both the magnitude and timing of changes in these climatic factors. Agronomists have long studied these interrelationships and developed models to predict crop yields in response to changes in climate. The predictions from the GCMs can be combined with these agronomic models to produce estimates of yield changes under different future climate regimes.

Most previous studies of the impact of climate change on agriculture have stopped there. However, several key ingredients are missing. As most of us know, farmers are astute entrepreneurs. They are not likely to be passive in the face of such change, but rather will adjust and respond to market forces. Crop locations will shift and production techniques will be altered in response to market outcomes driven by the productivity changes.

In order to capture these economic responses, we have adapted a national model of agriculture originally developed by the Economic Research Service of the U.S. Department of Agriculture (Horner, et al., 1985). Coupling this economic model with crop productivity changes allows us to estimate both the role of market forces and the resulting geographic cropping patterns.

Although only one climate scenario from one GCM was analyzed (the GISS scenario A), different assumptions concerning the crop productivity effects of those climate changes were estimated. Crop yields will be affected by 4 main factors: temperature, CO_2 concentration, evapotranspiration, and precipitation. While minimum temperatures are necessary for crop growth (see Figure 1), temperature increases will be the main source of yield reductions. Soil moisture changes from altered precipitation patterns and temperature increases will also be an important determinant of yields. CO_2 concentration increases will have an inadvertent fertilization effect and tend to increase yield. However, crops vary in their ability to use the increased CO_2. Corn and sorghum, for example, would benefit less than other crops. Thus, the relative impacts of both climate and atmospheric changes will vary by crop. Agronomists are currently working to integrate both effects in their models of crop growth. Crop productivity impacts for this study were taken from a range of estimates in the published literature and are cited in the report submitted for the record. The study reported here today analyzes CO_2 and climate change effects separately and then combined.

Figure 1. Production Rates for Crop Groups by Temperature



Source: Doorenbos and Kassam (1979), p. 12

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SUMMARY OF RESULTS

The yield reductions evaluated in this study varied among crops and scenarios. For example, in the corn belt, corn yield reduction were estimated to range from 22-27% depending upon whether CO_2 effects are included or not. Experts in that region have been recently quoted as predicitng a drop of 11% in national average corn yields currently (Maidenberg, 1988). Other crops currently affected by drought, wheat, oats, and barley, are also expected to suffer yield reductions ranging from 1-25% depending upon location and CO_2 effect. Soybean yields are estimated to span a range between 0.5-27% lower.

In the aggregate, these yield changes were estimated to cause a loss in economic welfare from agriculture of between $0.6-$11.6 billion in 1982 dollars in average annual terms. In contrast, current estimates of the effects of the drought are approximately $3 billion for three major crops (Associated Press, 1988). The estimates of damage to agriculture from ther environmental problems are also useful comparisons. Tropospheric ozone or smog is estimated to cost the agricultural economy approximately $2 billion annually (Adams and McCarl, 1985. Stratospheric ozone depletion and the increased ultraviolet radiation that it would generate would cost about $2.5 billion (Adams and Crocker, 1987). The climate change impacts upon agriculture can be several times larger than the damages caused by these environmental stresses.

While the economic welfare effects may be substantial, Americans are not expected to have difficulty feeding themselves. Foreign consumers will face the bulk of the supply reductions as exports contract due to reduced supplies. Figure 2 displays the aggregate national production changes estimated under the alternative scenarios. Wheat, barley, and oat production is currently expected to be reduced by 22% as a result of the drought (Schneider, 1988). Under climate changes, barley production is estimated to decline between 1-19.5%, while wheat would be off 1.5-7%, and oats from 1-14%. It is important to remember that the results of this analysis also allow for long-run shifts in the location of crop production in response to changes in competitive advantage, whereas the drought impacts are shocks to crops and investments in place and so reflect short-run impacts.

The severity of the current drought for the corn crop will be determined in the next 10 days as we enter a critical phase of crop development. The number of days above 95° F have been shown to be a critical determinant of corn yields (Mearns, et al., 1984). Corn is expected to be severely affected by climate change due to its relatively poor utilization of CO_2 increases. As shown in Figure 3, corn production could decline between 9-14%.

Production declines will be met by price rises, a phenomena we are witnessing now in agriculture due to the drought. Soybeans have hit their highest price in 11 years. On the futures market July soybeans have jumped nearly 100% this year. July corn is up 72% and September wheat has risen 55%. The price changes predicted in this study under some scenarios are roughly the same magnitude (see Figure 3). Much of the concern about these price hikes focuses on their impact in rekindling inflation and weakening the confidence of financial markets.

Figure 2. Aggregate Crop Production Changes

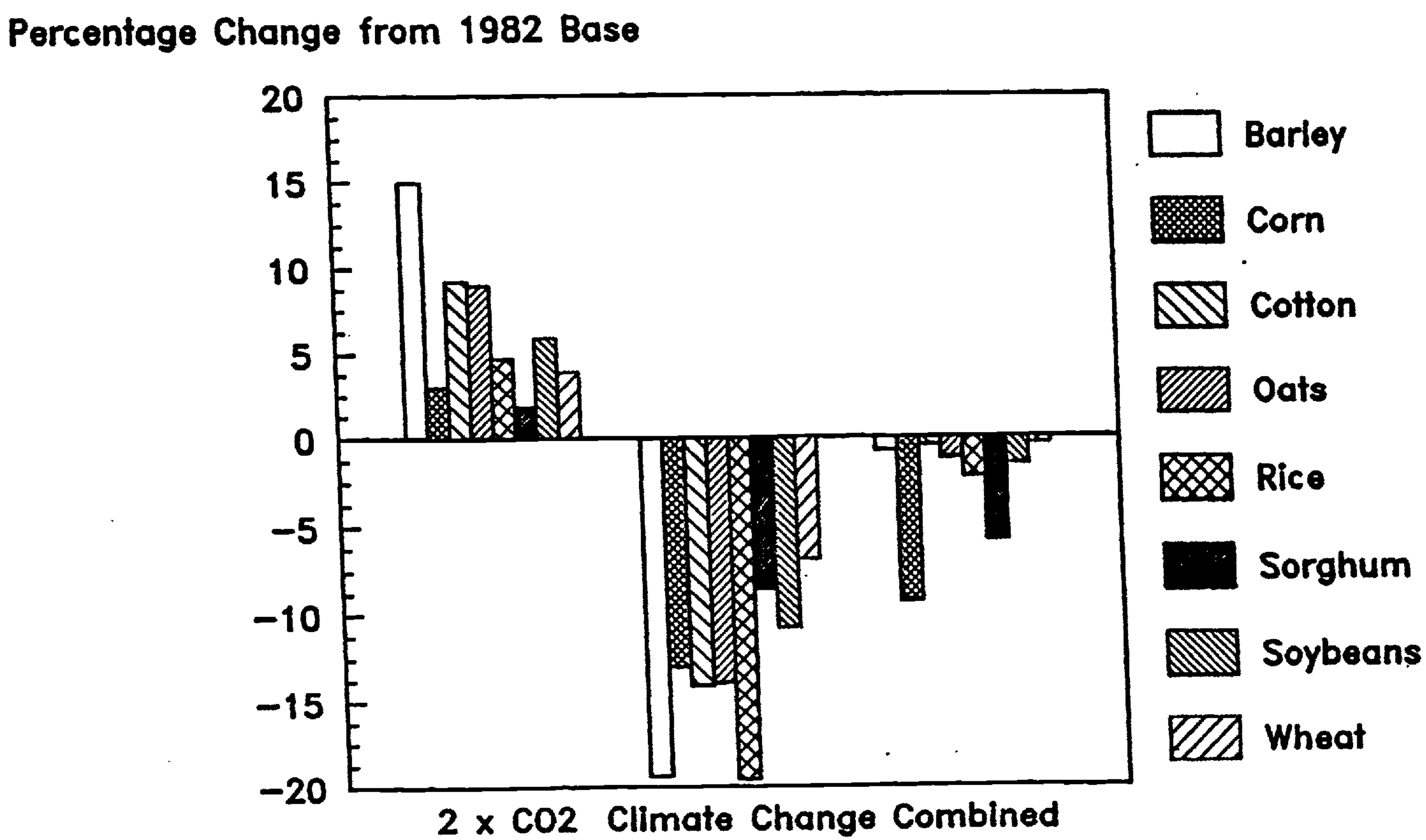
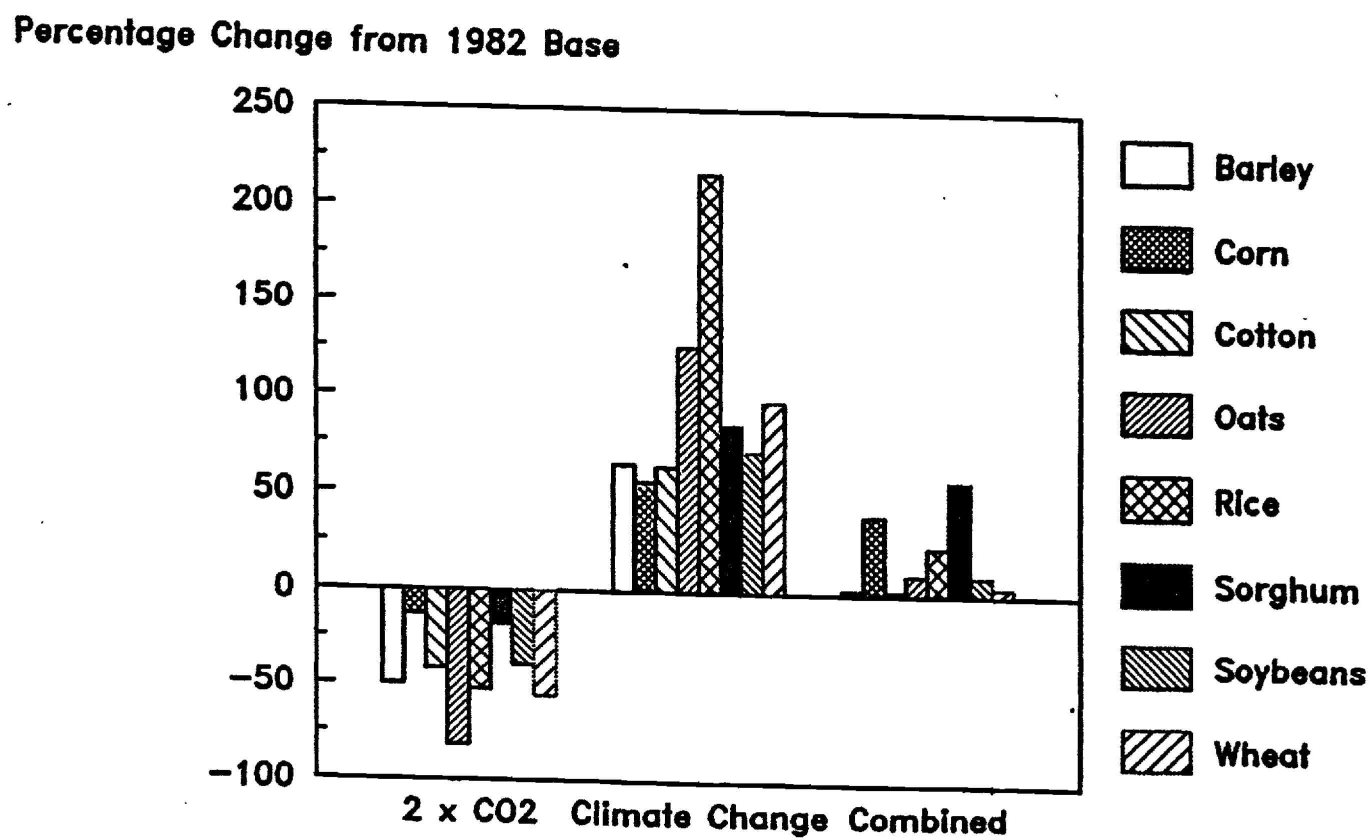


Figure 3. Aggregate Crop Price Changes



REGIONAL CHANGES IN CROPPING PATTERNS AND RESOURCE USE

The results previously described are generally robust in the direction of changes that they describe. Similar studies being prepared under the Global Climate Protection Act, in their preliminary form, describe the same patterns across a wider of GCMs, scenarios, and more detailed crop productivity assessments. One of the more notable general results is a geographic shifting of agriculture and a shift to irrigation. Figures 4-8 decribe these acreage changes. Note that in Figures 4 and 6, substantial increases in dryland acreage are estimated. These are exactly the regions that are being hit hardest by the drought. As indicated in the limitations section of this testimony, precipitation and soil moisture impacts of the sort described by Manabe and Wethereld (1986) were not included in this analysis. In those that have included these changes, the shifts described here are intensified and the losses greater.

One of the important shifts that might occur under these conditions is an intensification of irrigation throughout the nation, but particularly in the northwest and northern Great Plains (see Figure 8). While increased irrigation particularly from groundwater has been a historic response to drought conditions, it is uncertain whether groundwater resources in the future will be economically available. Current incentives to farmers encourage groundwater mining in excess of recharge rates. Future physical supplies of the resource into the future are uncertain on this basis alone. Further, the impact of changes in precipitation and runoff in a greenhouse world have not been determined for groundwater. Energy prices are also an important determinant of the economic feasibility of groundwater pumping and

Figure 4. Eastern Dryland Crop Acreage Changes

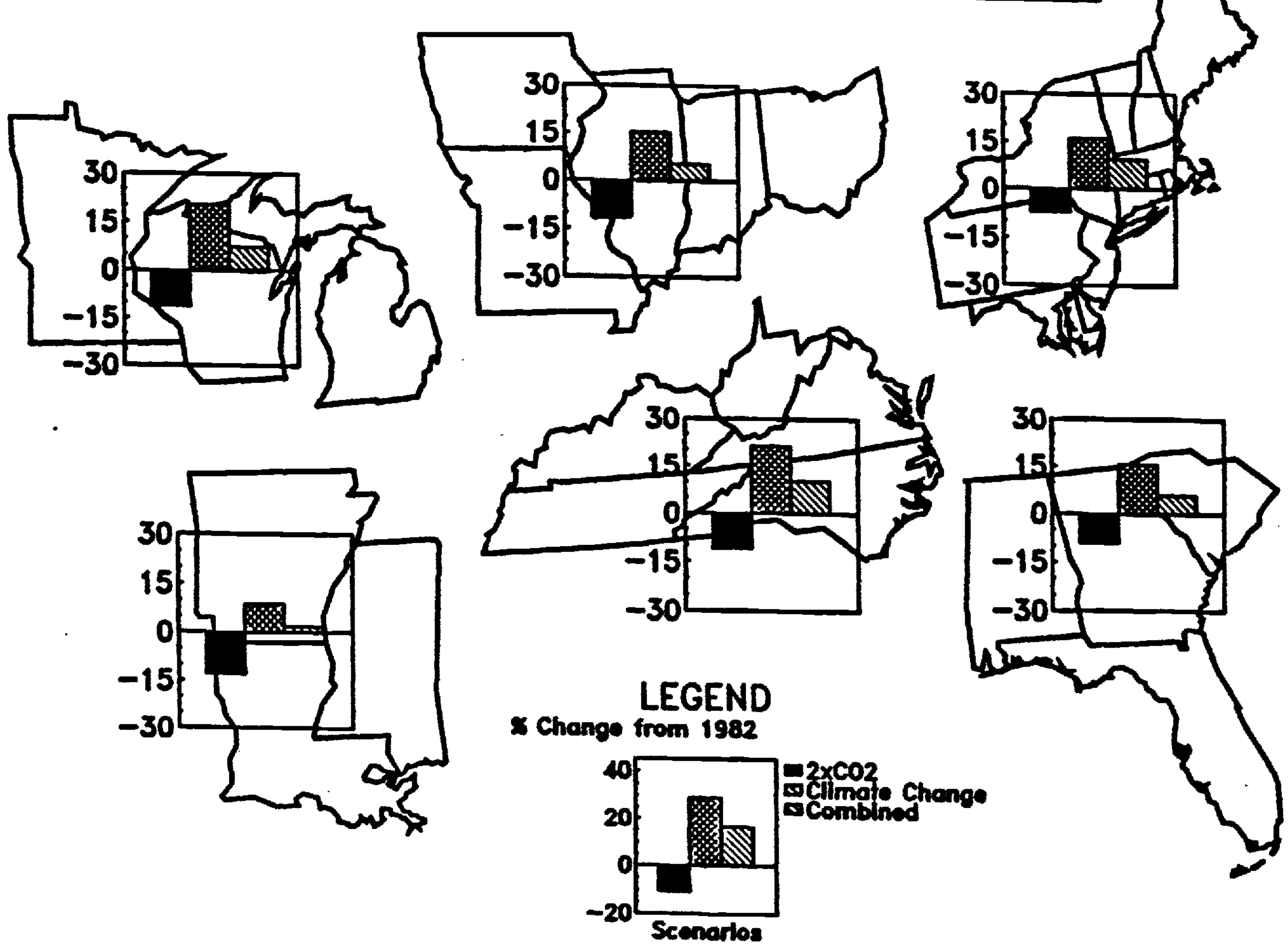


Figure 5. Southwestern Dryland Crop Acreage Changes

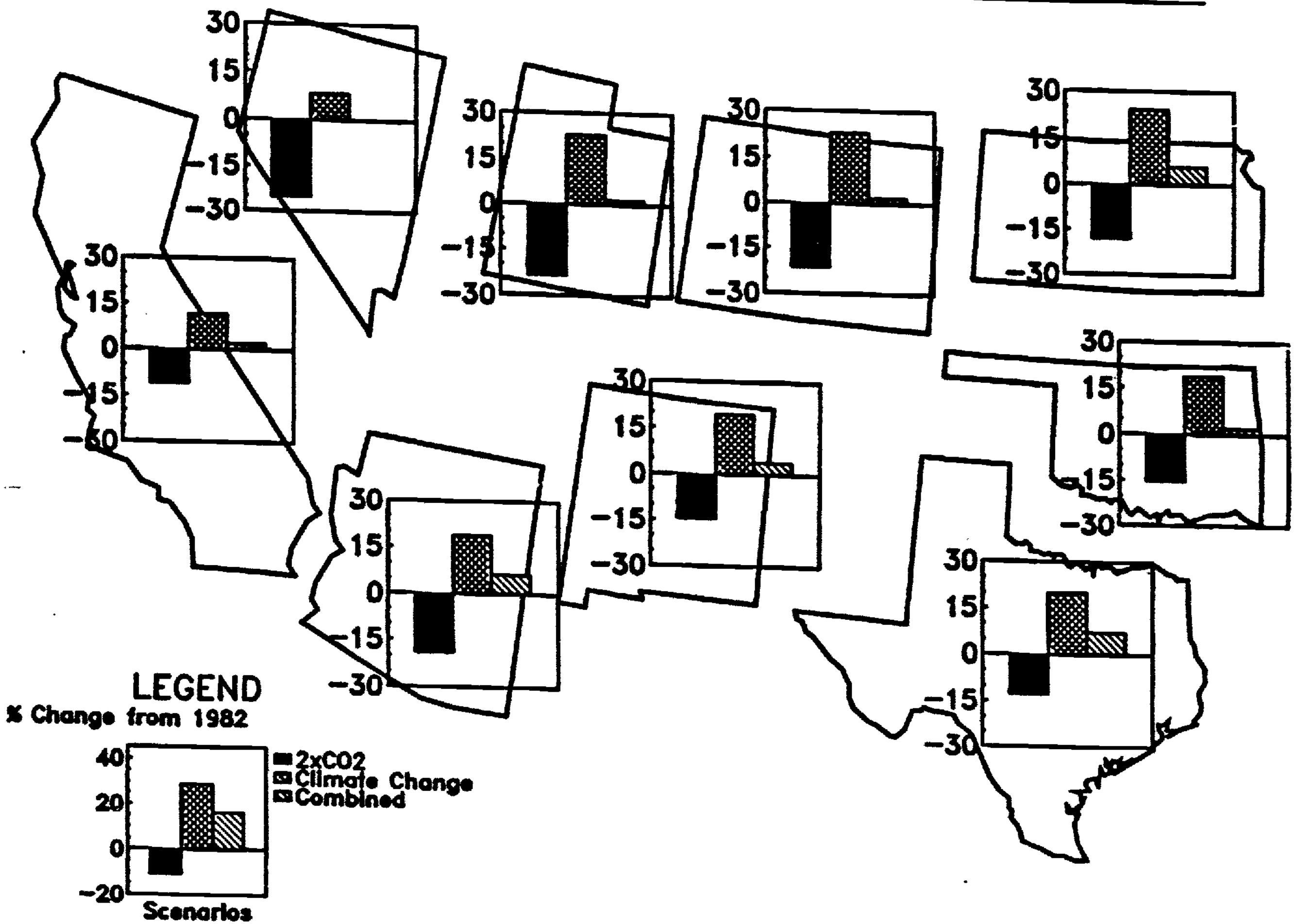


Figure 6. Northwestern Dryland Crop Acreage Changes

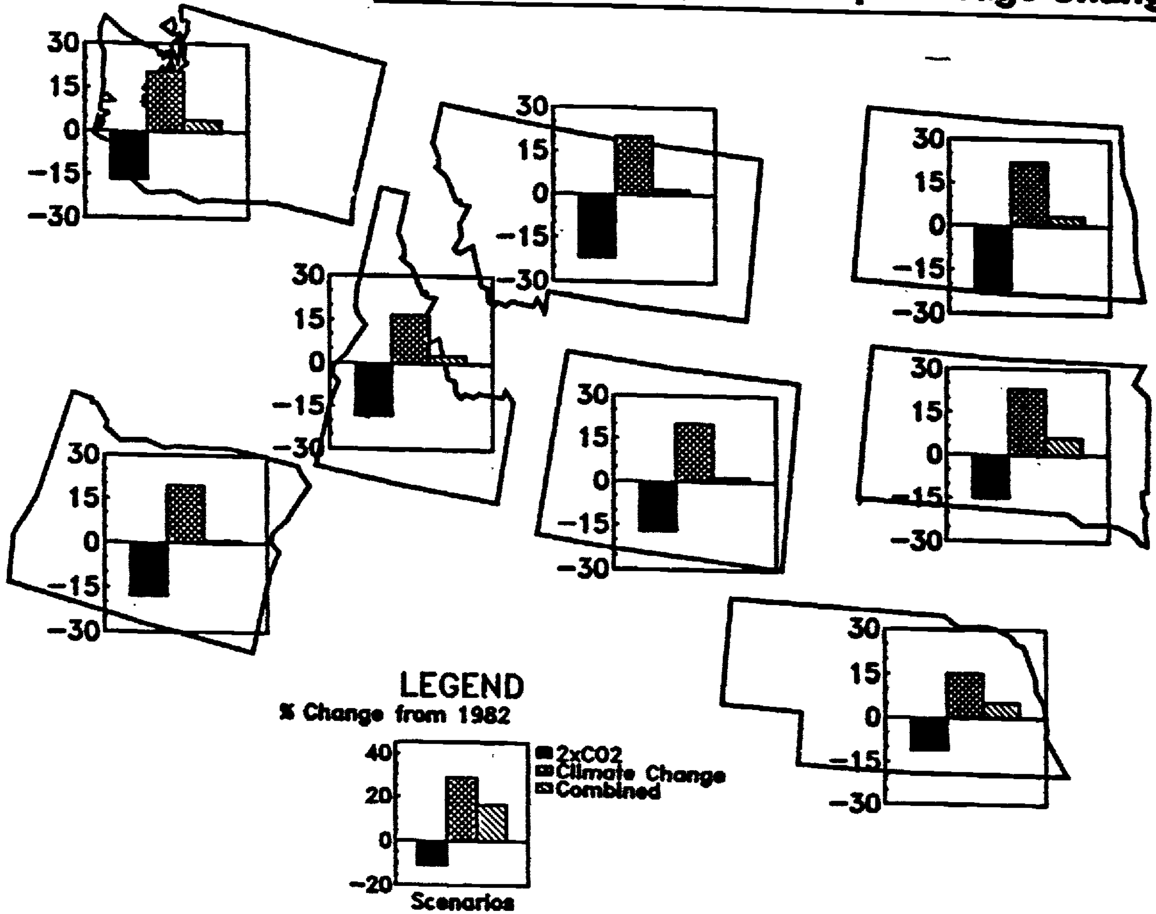


Figure 7. Southwestern Irrigated Crop Acreage Changes

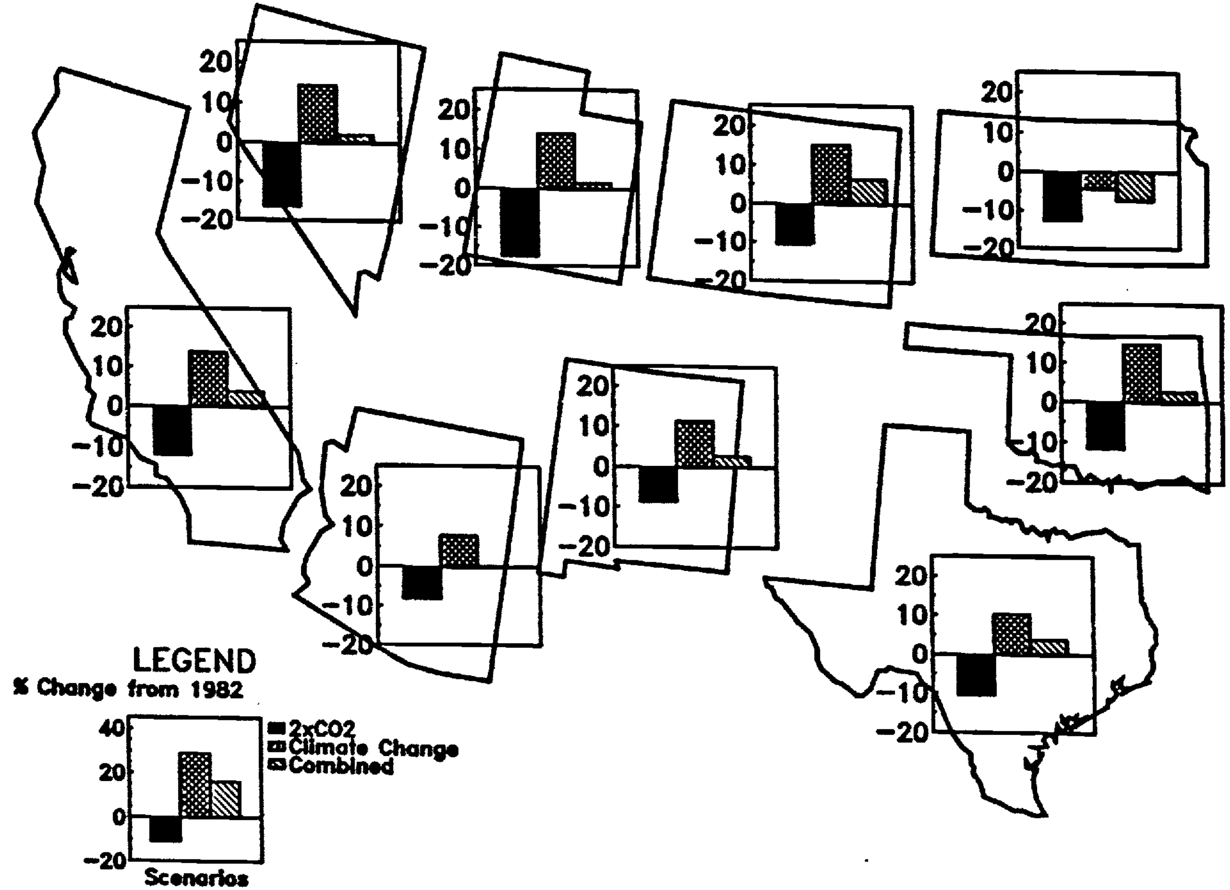
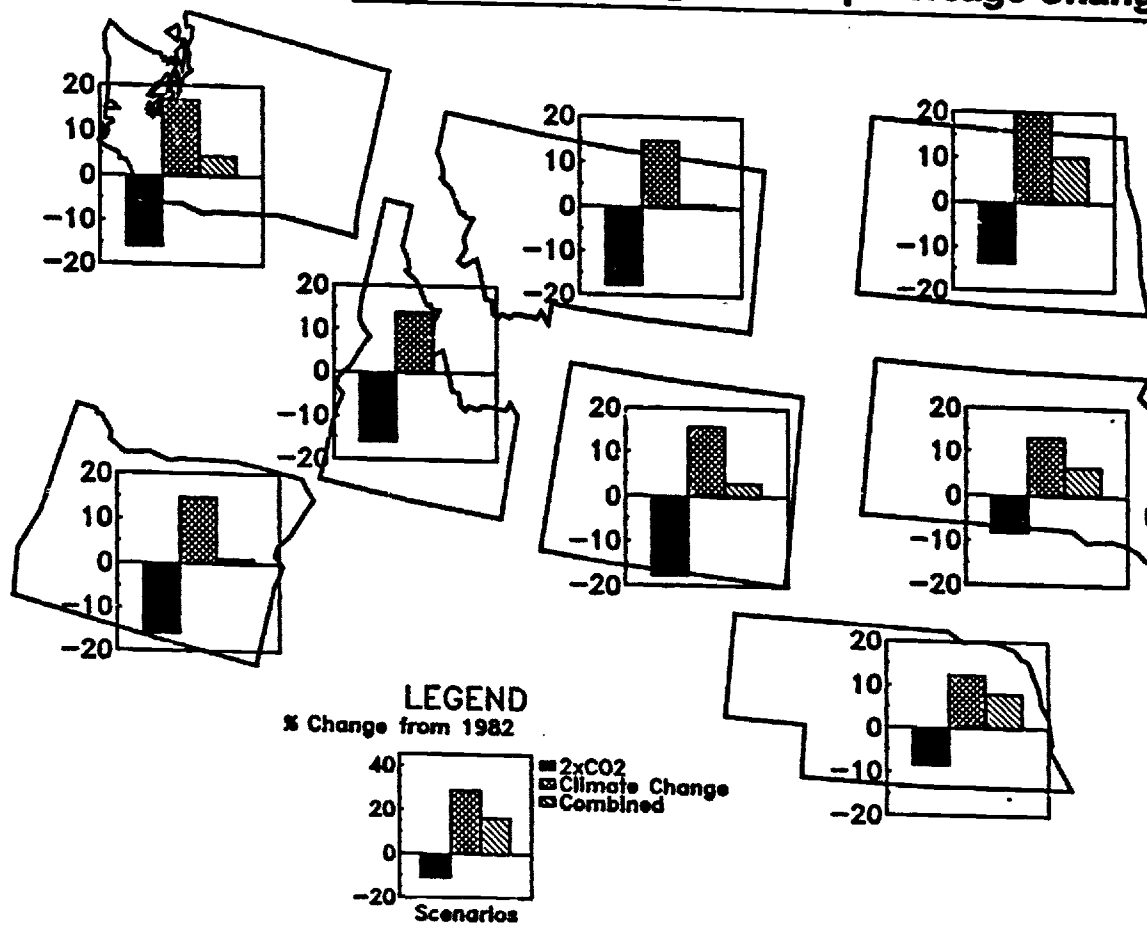


Figure 8. Northwestern Irrigated Crop Acreage Changes



present another critical element of uncertainty which could limit the effectiveness of irrigation in mitigating climate change impacts.

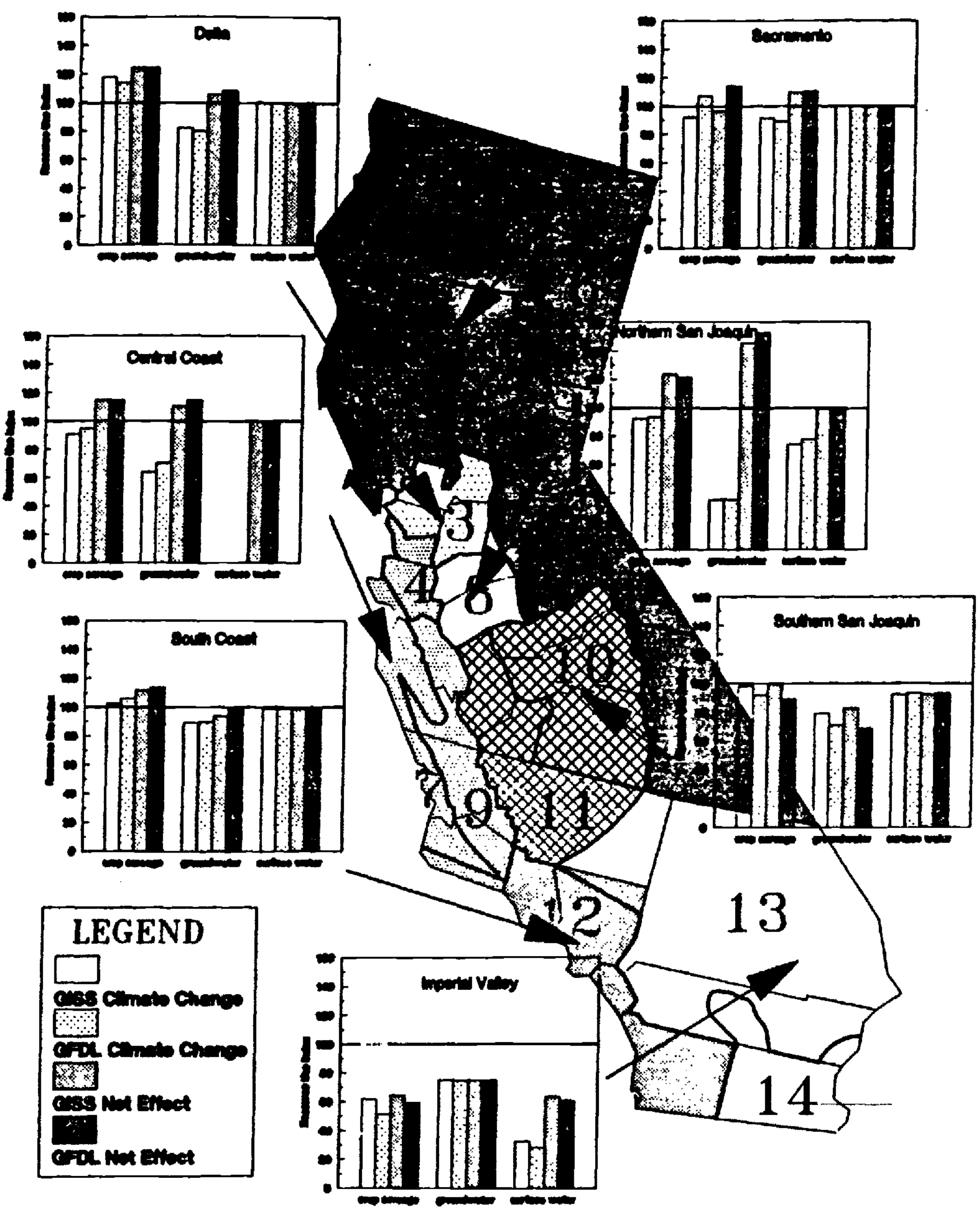
WATER SUPPLY AND INVESTMENT

The shifts to groundwater are illustrated in Figure 9 which displays the results of a similar analysis focused on the state of California alone. The Central Valley regions (Sacramento, Northern andd Southern San Joaquin) show marked changes in groundwater use. In part, these are driven by changes in surface water supplies. Although runoff is expected to be increased, it cannot be captured by existing facilities built upon assumptions of an unchanged climate. The result is average annual reductions in state water project deliveries of 25-28%. At an average cost of $500 per acre-foot, a rough approximation of the value of the investment in California water projects alone is $15-20 billion. An important question underlying the geographic adjustments previously described is whether new investments of this magnitude are possible given the controversial nature of dams.

Public strife over water is not new, but climate change could raise it to a new level. The controversy surrounding the proposed Two Forks Dam in Colorado is an good case in point. Opponents have called the project a "dinosaur". Giben the predicted impacts of the greenhouse effect, we might well ask whether climate change will resurrect the dinosaurs.

The critical importance of water to agriculture is also demonstrated by the transportation bottleneck caused by low Mississippi River flows. While agricultural development in adjustment to climate change may not be limited by land, infrastructure such as transport and water supply may be lacking

Figure 9. Regional Resource Changes



and limit such adjustments.

LIMITATIONS

The results presented in this testimony are computer experiments designed to describe the current agricultural economy if it were subjected to the types of climate changes predicted from the GCMs. No attempt has been made to forecast agricultural technologies of the future. The tastes and preferences of consumers are those expressed today. Exports are maintained at present levels despite the fact that climate change is a global phenomenon which affect agricultural regions around the world and thus the international markets for commodities.

Resources essential for agricultural production such as water and land will also be affected by climate change. For example, warmer temperatures will alter the mix of precipitation between snow and rain as well as shifting the timing of the spring melt. In western regions dependent upon irrigation, the loss of reservoir storage provided by the snowpack can mean reduced water supplies. Even if stream flow is increased in some locations, existing reservoirs have been sized to match the size and timing of historic flows. Increased early season runoff would force water supply operators to increase releases downstream in order to maintain the flood control capabiliites of their facilities. Changes in precipitation and runoff patterns will also affect groundwater recharge and availability. None of these water supply impacts have been included in this study, although estimates of changes in groundwater pumping are made. Similarly, land resources are presumed to be available for agricultural production.

CHALLENGES AND IMPLICATIONS

Technical Change and the Importance of R&D Investments

Another useful way to think of the implications of the agricultural changes that could occur is to relate them to the changes in productiviy that we have observed in the past. Over the past several decades agricultural productivity in the form of increased yields has averaged about 1 3/4% per year. For some crops under some of the scenarios, sustaining this rate for more than a decade would be required to roughly balance the negative productivity impacts.

The importance of research and development investments was one of the critical lessons from stratospheric ozone protection efforts. The scope of feasible policy actions had been significantly expanded by private investments in the 70's to investigate alternative chemical formulations. The existence of these alternatives reduced the threat of radical lifestyle changes and eased the way for international agreement.

The limited responses available to policy makers concerned with the drought demonstrate the importance of developing choices well before they are needed. In addition, including climate change among the reasons for action on other environmental problems is only prudent. Given the importance of market signals to all actors in the economy, distortions in those incentives whether due to market failure or government intervention should be removed if we expect private citizens to make informed decisions. For example, linking income transfers to agriculture to production maintains more resources in agriculture and increases the stakes in the climate gamble. Efficiency in water can be encouraged by promoting the development of water markets. Such markets would improve present efficiencies, reduce pollutant loadings, and facilitate resource transfers in response to climatic change. The failure to include environmental effects as a factor in public utility investment decisions concerning energy production also increases our risks. End use and generating efficiencies would be improved by this change. There are many good reasons to hedge our bets, not the least of which is the damage mounting up in the Middle West.

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Senator WIRTH. Thank you, Dr. Dudek.

Finally, Dr. William Moomaw. Bill, thank you for being with us.

STATEMENT OF DR. WILLIAM P. MOOMAW, DIRECTOR, CLIMATE, ENERGY, AND POLUTION PROGRAM, WORLD RESOURCES INSTITUTE

Dr. MOOMAW. Senator Wirth, I want to thank you for the opportunity to testify at this hearing.

The testimony by those who have preceded me represents a truly remarkable consensus. The evidence is quite conclusive that carbon dioxide and other greenhouse gases are increasing as the result of human activity. The majority of this increase, it is agreed, is related to fossil fuel combustion, and additional amounts of warming may be occurring as a result of the release of chlorofluorocarbons from deforestation and from agricultural practices.

The data presented by Dr. Hansen convincingly demonstrates that the global average temperature is, indeed, rising by an amount that exceeds expected fluctuations from the climatic mean. The implication of this analysis is that the global climate is warming. For some who may not be as familiar with statistical analysis, the question remains how confident can we be that this is really the case.

As a physical chemist who has carried out basic research in the laboratory over the last 24 years where I can control all the variables, I expect to get data that is good to the 95 to 99 percent confidence level. From the work I have done over the last half a dozen years on acid rain out in the field, I feel fortunate when I see a correlation that is in the range of 60 percent of probability that that is not a chance event. So, for his analysis to show a deviation with 99 percent certainty is remarkable, at least in my experience in terms of measurements that are made out in the environment. At least in statistical terms, it is a very impressive correlation, and it is very convincing.

But in some ways these facts—because I think the temperature rise and the gas rise are really facts that are not really debated—still beg the question. Is there a link? Can we establish a definite link between the rise in the greenhouse gases and the rise in temperature? You have heard evidence here from several of the witnesses, including those who were involved in the Bellagio-Villach meetings, that concludes very strongly that, indeed, a link does exist, that there is a strong body of convincing evidence that we are heading into an early greenhouse effect, and that warming rates exceed anything that we have ever experienced before by a large margin.

Now, I realize that there are people who are still doubters, and I think it is always healthy. Having been through the ozone depletion issue in the mid-1970's, as have Senator Domenici and Senator Bumpers, I'm aware of this problem. How do we make decisions which have potentially enormous consequences in the face of some uncertainty?

Well, let me suggest that in this particular case, if I may use an analogy, that the findings to date suggest to me that our society is like a high-speed automobile that has just seen a traffic light way down the road change from green to amber. I would argue that what we should do—we have two impulses when that happens. The first, of course, is to step on the gas and see if we can beat the light. I would suggest that we not follow that impulse, that instead of doing that, that we slow down. And if we are fortunate enough and we slow down in the right way, the light may again turn green by the time we reach the intersection. If we don't follow that strategy, we may get to the intersection and our whole economy may be up against a full stop.

I believe that we can begin now, even with the uncertainties, to begin taking precautionary action. These actions need not be drastic. They need not be disruptive of our economy or of the economies of other nations of the world. Some of these actions are already underway and many of them will have multiple benefits.

It has already been mentioned, for example, that chlorofluorocarbons contribute to the greenhouse warming effect. Now, the Montreal Protocol says that we will all agree to cut these by 50 percent by 1999. One of the things we have to be certain of is that the gases that will be substitutes for the chlorofluorocarbons that we are now using, which will be designed to protect the ozone layer, that those gases, those substitutes, will not be released into the atmosphere in a way that will increase the greenhouse effect. There has been virtually no discussion of that particular possibility, and I think it is a matter of some concern. We could accelerate the rate at which we phase out chlorofluorocarbons, and we could also recapture and reuse chlorofluorocarbons.

I am shocked to discover that every spring I get a notice from my automobile dealer urging me to come and have my air conditioner flushed out and to have the chlorofluorocarbons replaced. That is an absolute, total waste of chlorofluorocarbons in most cases because most air conditioners don't need to be flushed out. They only need to be flushed out if there has been a problem. And yet, it's a very effective way of marketing additional chlorofluorocarbons.

So, there are very simple things we could do to reduce chlorofluorocarbons, not that that one item is going to solve all the problems. But there are some things like that we should take a look at.

Promoting energy efficiency has been mentioned as an option that we should be engaged in. Certainly it is the fastest and most cost effective method of reducing the rate of carbon dioxide emissions, and it's essential to use our fossil fuels more efficiently. And I think we have to look at both end-use efficiencies, lighting, automobiles and the like, as well as production efficiencies. And there are some very exciting new technologies which will mark the production of electricity, for example, much more efficient than it is now even when we are using highly carbon dioxide producing fuels such as coal.

It is sobering to note that an average new American automobile which meets the CAFE standards, if driven 10,000 miles a year, which is roughly the average that a car is driven in this country, that during the year it is being driven, it will release into the atmosphere its own weight in carbon as carbon dioxide. It's an enormous amount, on the order of a ton or more of carbon, that will be released. Yet, we know that there are cars being sold in this country right now that get double the gas mileage of the CAFE standard, and there are additional automobiles in the prototype stage which are on the road now, unfortunately mostly in other countries, that can get three or four times the gas mileage of the CAFE standard in the United States.

I should point out that energy efficiency may, in fact, improve our productivity. Japan produces a dollar of gross national product, or the equivalent in yen, with using about half of the energy per dollar of GNP as we produce. And I think there is a lesson in that in terms of their efficiency.

We need to move fairly rapidly into renewable energy technologies. We need to accelerate the development of those. And I think it is an obligation for wealthier nations like the United States to carry out the necessary research. We have cut way back in that kind of research over the last few years. Yet, it is very clear that the United States and a few other nations are the only ones who can afford to do that kind of research into renewable technologies that do not add to the greenhouse effect.

Not only will this investment increase our economic competitiveness, but it will also make possible the economic development of third world countries.

And I might just add that since I put this testimony together, I was speaking with Gus Speth, who is the president of the World Resources Institute who is just back from a trip to Japan and China. And he had a meeting with people in Japan at MITI, which is the organization that has been so successful in bringing together government and business in Japan. They are actively beginning to think in these terms and are viewing this as a potential market. That is, if the greenhouse effect is really going to be a major issue, they see themselves poised as having the products, the energy efficient automobiles, the energy efficient light bulbs, for example, which unfortunately are not made in this country, but are made in Japan and Europe, to be able to move into those markets very rapidly. And they see it as a business opportunity. I think there is, again, an important opportunity for us economically in the same way.

We need to examine fuel switching and the efficiency with which we use high carbon-emitting fuels. As I'm sure all of you have heard before—and I know that Senator Ford may not be happy to hear this again—that coal produces about twice the carbon dioxide for the amount of energy that we obtain from it as does natural gas. It is clear that we are not likely to stop using coal, since it is our most abundant fossil fuel, but we should probably think in terms of reserving the use of coal for ways in which it can be more efficiently used. If we attempt to move in the direction of synthetic fuels, the problem becomes even worse. And particularly if we make synfuels from coal, we end up producing in many cases three or three and a half times the amount of carbon dioxide per unit of energy that we get back compared to natural gas.

I think it is important to take a look at pricing options because it is very clear that in terms of using fossil fuels efficiently, we use them much more efficiently when prices were rising rapidly than we are using them right now. We need to take a look at pricing options, tax options, fees, market options, that would be most effective in reducing the greenhouse emissions from particularly fossil fuels. And I think in this we could learn a great deal from the European and Japanese experience where the price of gasoline, for example, in West Germany is double that in the United States, and in Italy it is three times what it is in the United States. And virtually all of that is due to extra taxes. And it does have a significant effect on the rate at which we use these fossil fuels. That is obviously going to be controversial, but it is something that we really must take a look at and decide whether or not it is important to stop using as much fossil fuel. This is certainly one way in which we can help achieve that through the marketplace.

I would echo George Woodwell's statement that we need to look at forestry and reforestation as an important direction to go.

And in answer to an earlier question about nuclear power, certainly I think we should reexamine the nuclear option. But I think most people don't realize what a small fraction of total energy production electricity is in the whole world. No one of these things I am suggesting can solve the whole problem. Each one may be able to contribute something to it. And so, I think we do have an obligation to look at all of them.

To conclude, I would just say that the options I have suggested can be implemented as a precautionary means of slowing global warming while we increase our understanding of the issue. I want to emphasize that there is still a great deal of needed field and laboratory research in order to understand the sources of some of these greenhouse gases. As was mentioned by a couple of the earlier witnesses, we need to do considerable development of the climate models to make them better predictors because I think as this process goes along, we're going to be constantly wanting to fine-tune our policies and we're going to need those models in order to be able to know where we are and where we are heading.

Finally, we need to expand our monitoring efforts in order to detect at the earliest possible time an unequivocal connection between greenhouse gases and climate change. I think it has really been very dramatic what the discovery of the Antarctic ozone hole has done to people's willingness to accept depletion of stratospheric ozone from chlorofluorocarbons. And it is because there was a real measure out there that people could look at. Unfortunately, it is a measurement of a phenomenon that will—well, I heard a group discussing this. Someone said it would take 100 years to heal even if we stopped producing chlorofluorocarbons now. And Sherry Rowland who was there said, oh, you're an optimist. A hundred years is the optimistic view. We expect it will probably take 300 years before it will heal itself.

The greenhouse effect is likewise one of these largely, at least on reasonable time scale, irreversible effects. So, I think it is important that we make some changes now, to begin shifting resources within the fiscal year 1989 Federal budget to support research that needs to be done, and to begin attempting to implement some of these policy suggestions which I and others here have made. I think these strategies have the advantage that not only do they address the greenhouse effect, they also address acid rain, urban air pollution, stratospheric ozone depletion. And I think it is these multiple benefits that we will get by moving to energy efficiency, phasing out CFC's faster and so on to which greenhouse effect makes just a more compelling case.

I would agree with George Woodwell that we have an important opportunity for the United States to provide leadership on the full range of global change issues that face us, and that the changes that are being suggested will, in fact, help provide responsible solutions to the problems that have been raised.

Thank you, Mr. Chairman.

[The prepared statement of Dr. Moomaw follows:]

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Testimony of

Dr. William R. Moomaw, Director
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World Resources Institute

presented before the

Committee on Energy and Natural Resources
United States Senate

June 23, 1988

Senator Wirth, I wish to thank you for the opportunity to testify at this hearing.

The testimony presented by those who have preceded me represents a truly remarkable consensus. The evidence is conclusive that atmospheric levels of carbon dioxide and other greenhouse gases are rising inexorably as the result of human activity. The majority of this increase is associated directly or indirectly with the combustion of fossil fuels along with significant contributions from chlorofluorocarbon release, deforestation and agriculture.

The data presented by Dr. Hansen convincingly demonstrates that the global average temperature is indeed rising by an amount that exceeds expected fluctuations from the climatic mean. The implication of this analysis is that the global climate is warming. How confident can we be that this warming is really taking place?

As a physical chemist who has carried out basic research in the laboratory where I can control most of the variables, I am used to obtaining data that is correlated in some fashion at the 95-99 percent confidence level. My experience in field research on acid rain is that natural variability over which one has no control yields data that is, at best, significant at the 63 percent confidence level. Hence, Dr. Hansen's finding of a global temperature rise at his reported level of statistical significance is truly impressive -- and convincing.

But, in some ways, these facts beg the real question. Is the observed global temperature rise caused by the increased concentration of greenhouse gases?

The report which you heard from the Bellagio Villach meetings concludes that there is a strong body of convincing evidence that we are heading into an early greenhouse effect with warming rates that exceed anything we have yet experienced.

What these findings say to me is that our society is like a high-speed automobile that has just seen a traffic light far down the road change from green to yellow. I would argue that we should respond to this caution signal by slowing down rather than by accelerating and attempting to run the light before it turns red. To press the analogy further, if we slow down far enough in advance, the light may have again turned green by the time we arrive at the intersection. Otherwise, our economy may come up against a full stop.

I believe that we can begin to take precautionary action now. These actions need not be drastic, nor need they be disruptive of our economy or of the economies of the other nations of the world. Some actions are already underway and will have multiple benefits.

1. *Reduce Chlorofluorocarbons*

The Montreal Protocol on Substances that Deplete the Ozone Layer will reduce CFC emissions to protect stratospheric ozone, but we must be certain that the substitutes -- that may also be released into the atmosphere -- do not contribute significantly to global warming. We should also examine ways to capture and reuse CFCs and find ways to eliminate their use on an accelerated schedule.

2. *Promote Energy Efficiency*

The fastest and most cost effective method of reducing the rate of CO_2 emissions is to use our fossil fuels more efficiently. Both end-use and generating efficiencies can be improved greatly in the near-term. It is sobering to note that an average new American automobile driven 10,000 miles per year will release its own weight in carbon as CO_2 into the atmosphere. Yet cars getting double that mileage are for sale in the U.S. this year and prototype automobiles which are three to four times as energy-efficient are being tested on the road right now.

I should point out that Japan currently produces more than twice the GNP for each energy unit as does the U.S. so there is much we can still do in this area.

3. *Renewable Energy Technology*

We need to accelerate the development of renewable energy resources. It is an obligation for wealthier nations like the U.S. to carry out the necessary research. This will not only increase our international economic competitiveness, but will also make possible economic development in an environmentally sound way for third world countries.

4. *Fuel Switching*

We need to examine options for switching from high CO_2-emitting fuels like coal to low CO_2-emitting fuels such as natural gas. Since we will certainly continue to use coal, we should develop technology that will utilize it most efficiently. It is also critical to avoid synfuel programs which greatly increase CO_2 emissions above those produced by direct burning of coal, oil or natural gas.

5. *Pricing Options*

It is necessary to determine which pricing, tax, fee or market options will be most effective in reducing greenhouse emissions. We can learn a great deal from the European and Japanese experience of establishing fees which more fully incorporate the environmental costs of fuel use.

6. *Conclusion*

The options I have suggested can be implemented as a precautionary means of slowing global warming while we increase our understanding of the issue. I want to emphasize that there is still a large amount of field and laboratory research that needs to be done to understand the sources of several rapidly growing greenhouse gases. Considerable development of climate models also remains to be done so that we can better predict the consequences of the greenhouse effect in order to best shape future policies. Finally, we need to expand our monitoring efforts in order to detect, at the earliest possible time, an unequivocal connection between greenhouse gases and climate change. I would hope that shifting resources within the FY89 federal budget to support more global change research would be a high priority for the Congress. While we need to carry out more policy research, the options that I have suggested have multiple benefits in reducing climate warming, air pollution, acid rain and stratospheric ozone depletion. At the same time these strategies will improve American economic competitiveness and enhance our own domestic energy security. We have an important opportunity for the United States to provide leadership on the full range of global change issues that face us, and to help provide responsible solutions to the problems they raise.

Senator WIRTH. Dr. Moomaw, thank you very much. We thank all of you.

We have a number of Senators here, and we might move very rapidly into questions. Let me just first of all ask a short one of you, Dr. Hansen, and then ask others to comment if they would like.

I think the question that everybody is asking today with all of the heat and everything going on across the middle west and the southwest and so on is the current heat wave and drought related to the greenhouse effect. And a subpart of that is how sure are you of your response. [Laughter.]

Dr. HANSEN. Well, I mentioned in my testimony that you cannot blame a particular drought on the greenhouse effect. You can say, at least our climate model seems to be telling us, that the greenhouse effect impacts the probability of having a drought. And in particular I tried to emphasize that even in the late 1980's and the 1990's, the greenhouse effect is already large enough to impact the probability of having a drought in the southeast and the midwest United States.

Senator WIRTH. So, you would say that the heat wave and the drought is related to the greenhouse effect. Is that right?

Dr. HANSEN. Yes. If you look over a time period of, say, 10 years, the number of droughts you get in that period, it appears that it will be larger because of the greenhouse effect. But whether you get a drought in a particular year depends upon the weather patterns that exist at the beginning of the season, and that is a noisy phenomenon which is basically unpredictable. So, I can't tell you whether next year is going to have a drought or not. All that we are trying to say is that the probability is somewhat larger than it was a few decades ago.

Senator BUMPERS. Well, Mr. Chairman, if you would yield on that just to ask a slightly separate question on the same line. Is there a correlation between the warming and the amount of moisture we get? Are they tied together?

Dr. HANSEN. Yes. That is certainly true, and the answer is different depending on which part of the globe you're asking about. At low latitudes and at very high latitudes, the greenhouse warming will tend to increase the amount of moisture both falling and available on the surface. But at mid-latitudes, particularly in the summer, the answer seems to be the opposite, that there tends to be a mid-latitude continental drying which Dr. Manabe discussed in some detail.

Senator WIRTH. Dr. Oppenheimer, do you want to take a shot? Any of the others of you want to answer the question? I think it is a perfectly logical question to ask, isn't it? I mean, the American public is out there. It is getting very, very warm. They hear about the greenhouse effect. It's on the cover of Sports Illustrated. It is the lead editorial in the New York Times. It is in Fortune Magazine, the newest issue, a long study of the implications of this. And people are saying is, in fact, that's what's going on. Are we having the drought because of the greenhouse effect? And it seems to me we have to be in a position of saying yes, no. I suppose there's a maybe factor, or we say yes with a certainty of such and such a percent. You all do this day in and day out. Tell us how we respond to that question.

Dr. OPPENHEIMER. I think I would just sort of recapitulate and maybe restate what Jim and Suki have said which is that no one episode, no one drought, no one heat wave can be ascribed uniquely to the greenhouse warming so that that part of the question has to get a maybe.

But you have to approach the question in a broader context. Increasing frequency of drought and heat waves is the sort of change that we would expect as the world warms, and as Jim said, it is the sort of change we might already expect to occur more frequently. But as Jim has noted, as several of us have noted, the global mean temperature has risen over the last 100 years. Four of the last 7 years have been the hottest on record, and this year appears already to be headed to be the hottest on record. So, it is reasonable to assume that the greenhouse effect is here. It is happening. The warming has begun. It has started. But no one I don't think in their right mind is ever going to say this one climate event in particular is related.

Senator WIRTH. Do any of the others of you want to comment? Dr. Moomaw?

Dr. MOOMAW. Maybe one way of stating it is that certainly the events that we have seen in the 1980's and so on are consistent with all the predictions of the greenhouse effect. That is different from saying that any one event is, in fact, ascribable to it. But it is certainly consistent with the predictions that have been made.

Senator MCCLURE. Could I ask one question at this point, Mr. Chairman? I think the question is absolutely logical, and I think the probability answer is the right answer. But that doesn't explain the droughts of the 1930's. Was the drought in the middle 1930's a result of the greenhouse effect?

Dr. HANSEN. You will notice in the climate simulations which I presented we began the simulations in 1958. That was the international geophysical year. The measurements of atmospheric composition began at that time and have been accurate since that time.

It is more difficult to go back and simulate the 1930s because we don't know exactly how the climate forcings were changing. We don't know what caused the 1930s to be warmer than the preceding decades. So, it is really difficult to say what caused the droughts in the 1930s.

Dr. MANABE. May I comment? According to our modern calculations that these model generated drought which we get don't have to be due to greenhouse gases. So long as you have general warming, you tend to get more of a likelihood of getting mid-continental summer dryness. However, a magnitude of—the 1930 was the warmest. It happened to be a relatively warm period also, as it is at the present time so that from this sense that during a warm period you expect more likelihood of dryness. So, in that sense it is consistent with expectations.

However, when we look at the magnitude of drying which is induced by about a half of a degree Centigrade warming, which it was in 1930—and presently—the magnitude of drying is smaller than the natural fluctuation of the dry/wet cycle which is induced by natural cause, not by greenhouse gases so that these drying forces are not large enough to say that it is due to the greenhouse gases. However, I suspect that the likelihood of this type of mid-continental drying will increase as the warming gets larger and larger into the next centuries.

Dr. OPPENHEIMER. I would like to make one more point. One of the reasons you can get a couple of climatologists out here saying that the greenhouse effect has already been detected in some sense is the string of warm years and the general trend. This year, as Jim said, is much hotter than previous years so far. I think what you will need to get scientists up here to say this particular drought might be due to the greenhouse effect or it is likely. If this drought continues or gets worse or becomes the worse drought ever in some sense, then I suspect you would have more people ready to ascribe it directly to greenhouse warming.

Senator WIRTH. As a summary point, let me say I have read a lot of studies, met with a great number of the people in this field and have become convinced myself that the probability of a greenhouse effect having a significant impact is about 99 percent, and that what we ought to be doing is moving aggressively on programs of energy conservation, alternative energy sources, reforestation and so on, and that even if that 99 percent is wrong and the 1 percent is right, those policies of reforestation, alternative energy programs, energy conservation and so on are good for us anyway in terms of economic and environmental policy. So, no matter what we do, we are going to end up doing the right kinds of things if we can aggressively pursue that kind of a program as laid out in a lot of the recommendations that you all had today.

And I think it is in pursuit of that with the uncertainty that is out there and doing more research and getting a better sense of that, but we also have to start to understand very clearly what the alternatives are and the policy implications are going to be. And I think that is what we are about here.

Senator Ford?

Senator FORD. Dr. Hansen, explain something to me if you can. I live along the Ohio River and Ohio Valley. And that belt through there and the south has been getting drier and drier, but the winters have become severe. They are not the dry winters. We been having severe winters, and you find the ice and snow in Florida. But from that whole belt south, the winters are becoming very severe. Now, explain that to me versus the dry summer and the harsh winters.

Dr. HANSEN. I don't think that is very surprising. Now, the mechanism for the dry summers in our model is due to the tendency of the ocean to warm more slowly than the land which tends to set up high pressure in the summer over the east coast of the United States, and the circulation around the high pressure brings up warm air northward to the middle west and southeast region. Now, in the winter, as Suki showed on one of his charts, is quite a different story. And some warming in the winter, especially at low latitudes, tends to put more moisture in the air. And if you are in regions where temperatures are still cold enough for condensation, it is not surprising to get more precipitation and snowfall in the winter.

Also, it should be pointed out that the natural variability in the winter is much larger than in the summer so that the first place we look to see the greenhouse signal is in the summer. So, regardless of what effects you predict for the winter, you don't expect to see those as soon as you do for the summer.

Perhaps Suki would like to elaborate on that.

Dr. MANABE. There may be some exception in certain regions, but in general our model indicates that winter would become milder, particularly in high latitudes over Canada and the Soviet Union. And I understand over Alaska, winter temperatures have gone up much more than other places so that I understand your experience may not be typical—that is, winters are more severe—because there are many other places where winter has become milder, such as Alaska I understand.

Senator FORD. We are beginning to get the winters now that you used to have in the Great Lakes region.

Dr. MANABE. Pardon?

Senator FORD. We are beginning to have in our area the same type of winters that the Great Lakes region used to have 15 years ago.

You're going to expect some kind of policy from this group, and it will come out of this committee. And I would like to have as much knowledge and as much background as I possibly can.

Now, Dr. Moomaw, tell me which gives the atmosphere more problems. Natural gas or nuclear?

Dr. MOOMAW. Well, it is clear that natural gas gives more carbon dioxide emissions than nuclear power.

Senator FORD. So, you would suggest that we go to nuclear then.

Dr. MOOMAW. Well, not necessarily.

Senator FORD. Well, half of this group, I bet you, a few years ago was against plutonium. I suspect that many of them who are sitting at this table—or several of them anyhow—were against plutonium a few years ago. And now we have come 180 degrees.

Dr. MOOMAW. Well, not necessarily. I think there is a danger in all of these issues of viewing them one at a time. I think we have made that mistake just within the atmosphere alone of looking at the greenhouse effect as though it were something totally unrelated to the acid rain problem or the urban air pollution problem. And I think it is even more important that we not solve one problem at the expense of something else. I think we have to make a value judgment. And I think the value judgment on nuclear power is a very important one to make, and it has to be addressed.

I have argued that we need to reassess nuclear power in this country because I in all honesty do not see nuclear power in its present form going much beyond the current group of plants that are already scheduled to be completed.

Senator FORD. Since you were the only witness that singled me out by name, let me ask you a question. Is there any type of clean coal technologies that would solve your problem or this panel's problem as it relates to emissions of clean air because you are moving toward acid rain. I listened to you and that's the underlying bubble.

And I'm trying to find ways to use the resources that we have. We have an energy policy today that has been laid out pretty clear, and that is dependency. That is our energy policy today: dependency. And what I want to do is try to take the resources we have and quit depending on other countries. Now, how do we use the resources we have abundantly that would eliminate your problem as it relates to the greenhouse effect?

Dr. MOOMAW. I would certainly argue that the resource we have in greatest abundance in this country is the potential for using fossil fuels more efficiently. And I think we can actually move—and I will be glad to supply members of the committee with a study that makes this argument—substantially in that direction in the very near term at much lower cost than we can either by building any kind of additional power stations regardless of whether they are nuclear powered or fossil fuel powered.

In terms of coal technologies, which I think is your direct concern, there certainly are new coal technologies that are both cleaner and more efficient than the coal technologies we have been using.

Senator WIRTH. If I might just suspend for a moment. We have a live quorum and then a vote on the substitute on the plant closing bill. So, we're going to be I gather about 20 or 25 minutes. Is it the pleasure of Senators to come back?

Senator DOMENICI. I can't.

Senator FORD. I can't come back. I've got a 4:30——

Senator WIRTH. Do you want jump in very quickly before we go? Bill was answering that question. I'm sorry. We'll finish that answer for the record, if we might, Dr. Moomaw.

Senator DOMENICI. I wasn't here when you all gave your detailed statements and I am not one who is going to suggest that I had a chance to read them because I didn't.

I had an experience in this field, as you already know, many, many years ago quite by accident with Senator Bumpers when we were both assigned to an innocuous subcommittee that was given to us as freshmen, and it was going to disappear in a year. One of the assignments was the fluorocarbons, and we happened to find out then that we had some problems. And from that came the aerosol issue that was ultimately resolved rather beneficially here and I think it is beginning to be resolved worldwide.

To me it seems that we as a people and probably peoples all over the world are very skeptical to move in areas such as this until we either have a disaster or we have absolute concrete proof of something. And even when we have that, it seems that we need a game plan of some type. I mean, it isn't going to do a lot of good to theorize. We have some tremendous evidence that the earth is warming, and I guess the evidence indicates that that is surely going to cause some real problems for us and for the world. And I assume your testimony has indicated that you are getting more and more confident that that warming is substantially related to the greenhouse effect as it applies to gases going up and heat not being able to leave as it should. Am I correct to this point?

Dr. HANSEN. Yes.

Dr. OPPENHEIMER. Yes.

Senator WIRTH. Senator Domenici, we have seven minutes left on the vote.

Senator DOMENICI. Did you want to ask a question?

Senator WIRTH. No. I was going to adjourn the hearing.

Senator DOMENICI. Can I adjourn it and take my chances?

Senator WIRTH. Why don't you.

Gentlemen, thank you very much. We will be back in touch with you very shortly. I greatly appreciate it and we will leave this to Senator Domenici. Thank you, Pete.

Senator DOMENICI. You want to chicken out because you want to get there. You go ahead. I'll run there and get there. [Laughter.]

Senator Domenici [presiding]. I just want to finish this thought.

Therefore, we conclude that we ought to do what we can to inhibit the warming. Is that correct?

Dr. HANSEN. Yes, that's right.

Dr. MOOMAW. Yes.

Senator DOMENICI. Have any of you put forth a concrete proposal which I assume would involve both further investigations and a course of action? Have any of you individually or collectively put such a plan for further evolution of data accumulation and a suggested game plan that might be followed?

Dr. OPPENHEIMER. Let us answer that. This hearing was partly about a report which in at least a general way put forward such a game plan.

And I would like to—in response to Senator Ford's question which is really related to this, you don't think about solving the greenhouse problem by talking about whether we're going to have a total nuclear society in 50 years. That isn't the question. The question is what are we going to do tomorrow. We are not going to go 100 percent to nuclear energy tomorrow even if that were the only option, which it isn't. There are lots of other options, such as solar energy. The real question is what can we do tomorrow? And what we can do tomorrow, the first step is conservation and efficiency. Then let's worry about the longer term.

Senator DOMENICI. Let me just ask my last question. Is part of your assessment for us and for those who are trying to establish policy—is part of it also an assessment of the incremental increases in—or the opposite—incremental diminution in this problem by certain steps? Do we have that?

Dr. MOOMAW. Yes.

Dr. OPPENHEIMER. Yes.

Senator DOMENICI. So that if this happens we could expect a minimal positive response and that has been researched sufficiently where we have data on that.

Dr. OPPENHEIMER. Nothing is ever researched sufficiently, but the process is underway.

Senator DOMENICI. What I am very fearful of is that if we have a very difficult problem, it requires a difficult answer. The question is going to be asked regularly is whether that which we are being called upon to do is going to have an ameliorating effect and how do you know it is and to what extent. And if we can't get that kind of thing rolling, we are going to do a lot of talking, and we're going to do a lot of assuming, but we're not going to get this country or any country to take the kind of steps that are necessary. So, I assume the beginnings of a game plan or optional beginnings also carry incremental assumed benefits directed at this problem.

Dr. OPPENHEIMER. That's correct.

Dr. WOODWELL. Yes.

Senator DOMENICI. Thank you very much.

[Whereupon, at 4:15 p.m., the hearing was adjourned.]

APPENDIXES

APPENDIX I

RESPONSES TO ADDITIONAL QUESTIONS

ENVIRONMENTAL DEFENSE FUND

257 Park Avenue South
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July 27, 1988

The Hon. J. Bennett Johnston
Chairman
Committee on Energy & Natural Resources
Washington, DC 20510

Dear Senator Johnston:

Thank you for your letter requesting responses to questions pursuant to my 23 June testimony on the greenhouse effect. I shall respond in order.

From Senator Murkowski:

1) My remarks seem to have been misconstrued by the questioner. My reference to conservation epplies to conservation of nature, while Dr. Woodwell's refers to energy conservation.

According to several authoritative studies, energy conservation can achieve reductions from current use levels at a rate of about 2% per year up to a total reduction of about 50% in energy use (see Goldemberg, et al., Energy For A Sustainable World, and Energy For Development, World Resources Institute, 1987). Such reductions will not totally avoid greenhouse warming but would provide a good start at solving the problem and may save some money along the way, too.

Nuclear fission could provide a non-fossil fuel alternative to produce energy. But the safety, waste, and weapons proliferation issues associated with nuclear fission technology in its current form cast doubt on its ultimate technical and political feasibility. Instead, efforts should focus on the development of renewable energy sources such as solar photovoltaics. If private industry would like to pursue the nuclear fission option, exploring whether the aforementioned difficulties might be overcome, that option is open to them. However, given the scale of public subsidies to nuclear energy over the last few decades, and given its mixed record, future public funding should focus on R&D seed money for renewables.

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There is no physical limit to the potential of renewables as a substitute for fossil fuel. The limit is one of cost. The objective of an R&D program should be to bring down the cost. Nuclear, of course, faces this same obstacle, as well as several others.

2) At the current time, aircraft do not appear to play a significant role in either the greenhouse or ozone depletion problems. However, future fleet increases, changes in engine type or altitude of operation could alter this conclusion. As a result, the potential contribution of supersonic or hypersonic craft to ozone depletion in particular merits detailed investigation before any committments are made.

3) The specific research disciplines I would fund are:

a) ocean heat storage studies
b) ocean carbon cycle studies
c) ozone depletion studies, field and laboratory
d) long-term forest research
e) tree responses to pollutant/CO_2 enriched atmospheres
f) photovoltaics materials

From second list of questions:

1) The current drought and heat wave may or may not be directly related to the increasing greenhouse effect. Whether it is or not, the types of stress we are experiencing such as volatile commodity prices, low rivers, record smog and forest fires, are a foreshadowing of things to come if greenhouse gases are not constrained. Such episodes can be expected with increasing frequency from here on out.

2) We should obtain greenhouse gas reductions wherever we can. The problem cannot be solved without carbon dioxide limitation, but controls on other gases are also required. For instance, the Bellagio report notes that a reduction of about two-thirds in both CO_2 and non-CO_2 gases is needed to slow warming to the recent historical rate. Since half the warming comes from CO_2, a large reduction in that gas can have an important effect. So can a large reduction of the other gases in aggregate but not individually.

3) The global community should move toward developing a framework or convention for an international response. Such a framework would permit the assessment of scientific information and the evaluation of policy options. After a period of such assessment and perhaps a series of workshops, proposals for international protocols to limit emissions may be drafted.

4) We know of no limit to the warming as long as emissions of CO_2 continue at even half of current levels. Above that level, warming will be continuous, and there will be no steady state. Even a 50% cut may not be adequate to bring about a steady state. For the U.S., continuous emissions at current levels or higher means continuous change, loss of ecosystems, and probably loss of farm productivity, wetlands, beaches and coastal

infrastructure. The security of the nation depends on stabilization of the atmosphere.

I hope these responses are adequate. Let me know if you require further information.

Sincerely,

Michael Oppenheimer
Senior Scientist

MO:gp

Woodwell

Answers to the questions submitted by

J. Bennett Johnston
Chairman, Senate Committee on Energy and Natural Resources

Date: August 10, 1988

Question #1: Halting of global warming will require that the gaps between emissions and greenhouse gas sinks be closed. Do we have the ability to increase the earth's CO_2 sink capacity? If not, what percentage of the burden for controlling global warming will fall on reducing CO_2 and trace gas emissions?

Answer: There is currently a net accumulation annually of about three billion tons of carbon in the atmosphere. This three billion tons represents the difference between the total emissions and the total absorption by the oceans and the terrestrial biota. We do not know what the total absorption by the oceans and the terrestrial biota is globally; we know only the net accumulation. The most effective approach to reducing the imbalance appears to be a reduction in emissions, specifically a reduction in emissions from combustion of fossil fuels and from deforestation. If, however, we wished to increase the absorption of carbon from the atmosphere to speed the process of reducing the current imbalance, the most effective step would be to increase the area of successional or developing forests. An area of one to two million square kilometers of rapidly developing forest will store in plants and soils about one billion tons of carbon annually. The storage will continue for forty to fifty years until the processes of respiration and decay reach an equilibrium with gross photosynthesis. At that point there is no further storage. Destruction of the forest will release the carbon back into the atmosphere.

Various other techniques have been suggested, including the possibility of capturing stack gas effluents, compressing the CO_2 to make dry ice, and sinking the dry ice in the oceans. Such techniques require considerable energy and reduce the value of fossil fuels as a source of energy.

There is no alternative to a reduction in the sources of carbon dioxide and other trace gases.

Question #2: What changes do you feel must be made in park and wilderness area planning to adapt to warming that is already "in the bank"? What scenario do you forecast for the nation's public lands and wilderness areas in the next 50 years? 100 years?

Answer: Assuming that we move rapidly to stabilize the composition of the atmosphere and limit the global warming to the two degrees or thereabouts expected from the current increases in heat trapping gases, we can expect, in the middle and high latitudes, a change in the mean temperature of three to four or more degrees centigrade. Such a change is substantial and can be expected to produce changes in the climatic zones in the range of

100 to 500 miles with the greater changes in the higher latitudes. Such changes are enough to increase the mortality of trees substantially throughout North America and to start successional processes leading to quite different types of vegetation throughout much of the region. The fact that these areas tend to be insular, isolated from one another by agricultural or other developed lands, means that the migration of species between refuges is problematic. Specific steps may be required to manage biotic resources under these conditions. The steps will have to be developed within each region. The greatest pressures will occur in the next 50 years unless we are not successful in stabilizing the composition of the atmosphere. In that circumstance, there is virtually no action that can be taken to assure the continuity of natural communities. Forests , for instance, will be destroyed on their drier and warmer marginjs much more rapidly than they can be regenerated.

Question #3: The greenhouse phenomenon has been well documented, yet little has been said regarding the effect of climate change on our environment and landscape as we know it. Can you paint us a picture of what the farm belt or sequoias might look like in 50 years?

Answer: No simple diagnosis is possible. In general, areas that are now arable in the farm belt will become warmer and drier during the growing season. Climatic and edaphic zones now suitable for grain crops will migrate poleward; arid zones can be expected to expand in North America. There is, of course, no possibility of finding a new Iowa on the Canadian Shield.

I am not able to predict what will happen in a zone such as that occupied by the redwood trees that you refer to as sequoias. It is possible that the giant sequoias of the Sierra Nevada will enjoy a climate not greatly different from its current climate. The coastal region may be wetter. These, however, are speculative observations based on a very loose interpretation of meterologists' models, which are much too general to be used reliably in such a context. Changes in temperature, however, that lie in the range of 0.10 to 1.0 degree or more per decade are extraordinarily destructive of biotic systems. Large bodied slowly reproducing organisms such as trees are at a clear disadvantage. Forests are severely threatened. The action to correct such difficulties is to reduce the cause, the buildup of greenhouse gases in the atmosphere.

Question #4: Dire predictions have been made regarding the fate of U.S. island territories in the Pacific, nations such as Bangladesh, and states like Louisiana, if sea level rise takes place as believed. Are there any measures that can be taken to protect these regions? What time frame are we currently working in?

Answer: The most effective steps involve checking or deflecting warming. Whatever is done to reduce the warming will not prevent increases in sea level over the next 50 to 100 years. The increases are variously estimated as lying between 0.30 of a meter and 1.5 meters, possibly more. Dikes are expensive and not necessarily effective in areas as large and heavily populated as the Ganges Delta in Bangladesh. Recognition of the hazards of living in such places includes the recognition of the possibility of storm surges of novel proportions on a continuous basis. Such lands may have to be abandoned. Such is the cost of our current pattern of use of global resources.

Questions for the Panel, submitted for the record from Senator Murkowski.

Question #1: Dr. Woodwell suggests conservation as a means to reach the needed 40-60 percent reduction in fossil fuel consumption. Another witness Dr. Oppenheimer concedes that "the greenhouse effect" is so advanced that "the very concept of conservation does not exist in a world that may change so fast..."

- Can conservation alone achieve the necessary reductions?
- Is a greater reliance on nuclear energy one of our best alternatives to dependence on fossil fuels burning?
- If not nuclear energy, then what?
- What percentage of fossil fuel reductions can we reasonably expect from the alternatives you are suggesting?

Answer: I am uncertain of the basis of apparent contradiction presented by Dr. Oppenheimer, who agrees with my suggestion on fossil fuel consumption. Oppenheimer may have been referring to the conservation of natural communities including the management of parks and reserves. Management of such areas becomes very difficult under rapidly changing climate.

My statement about conservation dealt with energy. Improvements in the efficiency in use of energy and in the conservation of energy offer the very best hope for an immediate reduction in the emissions of the heat trapping gaees. A reduction in the use of energy from fossil fuels of the order of fifty percent is certainly possible over the next years in the industrialized nations simply by reducing trivial uses of energy, by conserving energy through insulation and the use of more efficient appliances, through improvements in the fuel efficiency of automobiles, and through systematic efforts to shift certain uses of energy to reliance on enduring sources, especially solar. The combination of conservation and improved efficiency with innovations in applications of solar energy can produce a 50% reduction in the total use of fossil fuels in the developed nations. In the lesser developed world the challenge may be greater in that the nations of the low latitudes see their futures as heavily dependent on increased use of energy. There is, however, no reason that the evolution of technology in those nations must follow the same patterns that it followed in the presently industrialized nations. There is every reason to believe that a much more efficient industrialization is possible with heavy reliance on solar energy. Such a transition will require further innovations in applications of efficiency in use of energy and in ways of harnessing solar energy. Those applications offer virtually infinite possibilities for industrial development.

Nuclear energy does not offer immediate promise in solving the heat trapping gas problem. Nuclear energy is very complicated, expensive, dangerous, and requires a long lead time for development. My present interpretation of the potential for nuclear energy is that a dollar spent on it would be much better spent in developing more efficient uses of solar energy. This conclusion is supported by a recent and detailed review of this topic by William Keepin of the staff of the Rocky Mountain Institute in Colorado.

I am especially troubled that the climatic change problem is likely to be used by the proponents of nuclear energy as the basis for arguing for a massive program in the redevelopment of the nuclear technology. Several factors argue against it. The most conspicuous is the expense. The least expensive energy can be developed through conservation and improved efficiency. My experience leads me to the conclusion that nuclear energy should play no role in this transition because of: 1) the intrinsic weakness of the technology, 2) our failure to find a solution to the high-level waste problem, 3) the hazards associated with the operation of reactors, 4) the current trend in technology that seems to be making energy production by large central power plants obsolete, 5) the dangers associated with terrorists, and 6) the fact that there is no way to guarantee that the very large inventory of radionuclides in reactors that have been operating for even a short time can be contained in a serious accident.

The reactor industry has promoted a most burdensome law, the Price-Anderson Act, that limits the liability of the industry and of government in the event of an accident. This law puts the burden of the accident on those that happen to be living near the reactor and are most likely to be affected by any release of radioactivity. Such a law offers the public no confidence whatever that the technology is as safe or reliable as the industry would have us believe.

Question #2: To what extent does fossil fuel used by aircraft contribute to excessive atmospheric carbon dioxide or ozone depletion? Does the fact that the fuels are burned aloft result in aircraft making a proportionately larger contribution to the problem than say, home heating, automobile emissions, or other "ground level" activities?

- Are there valid scientific reasons for limiting the development of supersonic or hypersonic transports or other aircraft that fly higher, farther and faster than current day aircraft?

Answer: The lower atmosphere, called the troposphere, is thoroughly mixed in a matter of weeks to months and it makes little difference at what elevation or in what region emissions occur. The upper atmosphere, the stratosphere, usually in excess of 30,000 feet, is partially isolated from the troposphere and noxious substances such as oxides of nitrogen emitted by high flying aircraft have a longer residence time there an a greater opportunity for interacting with the ozone layer. While I am not an atmospheric chemist and hesitate to offer a technical analysis of the chemistry of the stratosphere, I have had enough experience in following the problems generated by nuclear weapons and volcanoes to know that the introduction of particulate matter into the stratosphere in any form, as well as changes in the chemistry of the stratosphere, have far reaching implications for climate. I would take a most conservative approach in encouraging the further development of high flying aircraft that have the potential for affecting the composition of the stratosphere. The immediate challenge is to stabilize the ozone layer, a challenge that under the best of circumstances will require decades to a century or more. No steps should be taken that could in any way compound this problem.

Question #3: If you sat on the appropriations committee, and had the opportunity to appropriate funds for specific research disciplines, what would you fund if you wanted to get a better handle on this problem?

Answer: The immediate need is for a rapid reduction in reliance on fossil fuels. That reduction can come through conservation of energy. I would seek innovation in ways to reduce the use of energy in the industrialized societies. Those innovations can come through research in universities, various research institutions, and through agencies of government. Virtually every aspect of society is affected, not only those dealing directly with energy. I would seek to see the following supported:

I. Research on Energy:

A. Conservation: how to meet needs for energy with less; tax and other policies affect this realm. DOE, NSF, Dep't Commerce.

B. Efficiency: DOE, NSF programs designed to reduce energy use without reducing services. The research is far-reaching, involves standards of efficiency for household appliances and industrial equipment as well as technological innovation.

C. Solar: DOE, NSF
   1. Photovoltaics
   2. Hot water, air and other solar
   3. Energy storage systems, especially hydrogen

D. Wind, Tidal

E. Hydraulic

F. Other innovations

G. Biotic: NSF, DOE, USDA

II. Research on Energy Systems

A. Co-generation

B. Transmission Lines

C. Domestic and Industrial Systems

III. Research on Indirect Sources of Energy: USDA, DOE

A. Improved efficiency in water use, sewage treatment

B. Improved efficiency in transportation

C. Efficiency in Agriculture

D. Waste Treatment

E. Air conditioning living spaces

IV. Subsidies:

After study, subsidies are appropriate to speed the development of technology appropriate to support further economic development in the tropics.

V. Population Control:
Energy research and conservation measures are nullified unless population growth globally is slowed drastically.

There is an equally important list of steps to be taken to avoid doing further harm. Those steps include reducing subsidies for the further development of fossil fuel sources of energy. The need at the moment is to reduce the availability and use of fossil fuels. All governmental and international actions that encourage the use of fossil fuels should be reviewed and most of them revoked.

These are small costs in proportion to military expenses and in proportion to the cost of failure to stabilize the global habitat.

Submitted by:

G.M Woodwell, Director
Woods Hole Research Center

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August 3, 1988 R/E/GF

Honorable Senator B. Johnston, Chairman
Committee on Energy and Natural Resources
United States Senate
Dirksen Senate Office Building - Rm. SD-304
Washington, DC 20510

Dear Senator Johnston:

This is in response to your letter of 22 July 1988 requesting my response to your questions posed in connection with the hearing of your committee on global warming and greenhouse effect.

I have enclosed in this mail my responses to the two sets of questions from you and Senator Murkowski.

Thank you again for giving me an opportunity to testify before your committee on this important issue.

Sincerely yours,

Syukuro Manabe

Syukuro Manabe

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Response to the Questions from Senator Johnston

Syukuro Manabe

Q. 1) A great deal of attention has focused recently on the relationship between the current drought in the Plain States and the Greenhouse Effect. Do you feel that a correlation exists between the two phenomena? If so, what type of weather situations can we expect in the next 10 years? 50 years?

A. 1) In my testimony, I discussed how the warming of climate due to the future increase of Greenhouse gases induces a reduction of mid-continental soil wetness in summer. Since the increase of global mean surface air temperature during this century is only several tenths of a degree Celsius, the natural variation of surface hydrology can easily overshadow any summer reduction of soil wetness induced by the warming. However, it is likely that severe mid-continental summer dryness will occur more frequently as the warming becomes greater towards the middle of the next century. The current drought has given us a foretaste of what may happen in the future.

Q. 2) Could you explain the cloud feedback process to us in simplified terms? Could the Greenhouse Effect cause an increase in cloud cover through enhanced evaporation rates?

A. 2) Cloud cover exerts a cooling effect on climate by reflecting a substantial fraction of incoming solar radiation. On the other hand, it warms climate by reducing outgoing terrestrial radiation from the atmosphere. As the atmospheric circulation changes in response to the warming due to the future increase of Greenhouse gases, the global distribution of cloud cover changes in such a way that one of these two opposing effects overshadows the other, thereby enhancing (or suppressing) the warming. This interaction among clouds, radiative transfer and climate is called the cloud feedback process.

According to the numerical experiments conducted by various groups, the change of cloud cover accompanying the warming is quite complex. In response to the enhanced evaporation, the amount of lower level stratus cloud increases in high latitudes. However, the total cloud amount is reduced in middle and low latitudes. As the cumulus convection extends up to higher altitudes, the overall altitude of high cloud also increases. The net effect of these changes is an enhanced warming due to the cloud feedback process.

Unfortunately, the ability of current climate models to reproduce the global distribution of cloud cover is far from satisfactory. Although the CO_2-induced changes of cloud cover from various numerical experiments agree qualitatively with each other, they are quite different quantitatively. Recently, it has been suggested that the increase of liquid water content of clouds accompanying the warming may increase the reflectivity of the clouds, thereby reducing the warming. Because of the difficulty in modeling the cloud liquid water variation, this negative feedback effect is not incorporated in most of the current models. Our inability tc develop a realistic treatment of the cloud feedback process is one of the main reasons why our estimate of future warming has a large range of uncertainty.

Q. 3) Are some latitudes or regions of the United States going to benefit in terms of precipitation and soil moisture, from changes in the mid-latitude precipitation pattern?

A. 3) The impact assessment of a given climate change is not the topic of my expertise. Nevertheless, I feel it is important to make every effort to adapt to and exploit future climate change. In a warm climate with higher concentrations of Greenhouse gases, a larger fraction of precipitation is realized as rainfall (rather than snowfall) and snowmelt becomes more frequent in Canada and the Northern United States, thereby making soil wetter and increasing river runoff during the colder half of the year. As I noted in the text of my testimony, the snowmelt season begins earlier and snow cover disappears earlier in spring. It is likely that this information may be very useful in order to develop a strategy for future management of water resources.

Q. 4) Should we expect to see a dramatic increase in storm surges and hurricane activities as a result of global warming?

A. 4) Some theoretical analysis has suggested that the frequency of intense tropical cyclones may increase in response to the future increase of sea surface temperature; however, it is essential to confirm this suggestion based on a comprehensive set of modeling experiments before we can accept such a possibility. Encouraged by the success of our climate model in simulating the frequency distribution of tropical storms, we have devoted a major effort toward the study of the influence of greenhouse gas-induced warming on the frequency of tropical storms. At present the results from this study are inconclusive, but we are continuing to investigate this problem.

Response to the Questions Posed by Senator Murkowski

Syukuro Manabe

Q. 1) Dr. Woodwell suggests conservation as the means to reach the needed 50-60% reduction in fossil fuel consumption. Another witness, Dr. Oppenheimer concedes that the "greenhouse effect" is so advanced that "the very concept of conservation does not exist in a world that may change so fast..."

- Can conservation alone achieve the necessary reductions?
- Is a greater reliance on nuclear energy one of our best alternatives to dependence on fossil fuel burning?
- If not nuclear energy, then what?
- What percentage of fossil fuel reductions can we reasonably expect from the alternatives you are suggesting?

A. 1) I am not an expert on this topic and would like to refrain from responding to this question.

Q. 2) To what extent does fossil fuel use by aircraft contribute to excessive atmospheric carbon dioxide or ozone depletion? Does the fact that the fuels are burned aloft result in aircraft making a proportionately larger contribution to the problem than say, home heating, automobile emissions, or other "ground level" activities?

- Are there valid scientific reasons for limiting the development of supersonic or hypersonic transports or other aircraft that fly higher, farther and faster than current day aircraft?

A. 2) Again, I am not an expert on this issue. However, I solicited the opinions of Drs. J. D. Mahlman, (Director) and J. Pinto of the Geophysical Fluid Dynamics Laboratory of NOAA. Their response follows:

In the troposphere, commercial aircraft generate NO_x and CO, thereby contributing to the production of ozone. The expected increase of ozone due to this mechanism is consistent with the observed ozone increase of 1%/year in the upper and middle troposphere. It is also expected that such an increase of tropospheric ozone will contribute to the greenhouse gas-induced warming of climate.

Although the emission of NO_x from SST and/or HST can alter the concentration of ozone in the lower stratosphere, we prefer to refrain from discussing this issue pending a careful assessment by experts.

Aircrafts probably do not make any significant contribution to CO_2 emissions compared to surface emissions. They can lead to enhanced high cloudiness through condensation of vapor trails.

Q. 3) If you sat on the Appropriations Committee, and had the opportunity to appropriate funds for specific research disciplines, what would you fund if you wanted to get a better handle on this problem.

A. 3) An important research project which deserves high priority is the global monitoring of the coupled ocean-atmosphere-land surface system and the factors causing climate change. Such monitoring is essential not only for providing the input data for a climate model, but also for validating the predictions of the future climate change and its impact. Persistent and long-term support is required for this effort.

In addition to the monitoring discussed above, the improvement and validation of climate models deserve a high priority. Because of the limitation of computer resources, the spatial resolution of a current climate model is too coarse to satisfactorily simulate the geographical details of climate. Furthermore, some of the basic physical processes, such as the cloud feedback process and the ocean-atmosphere interaction are poorly understood and crudely incorporated in a model. Therefore, the dedications of major research effort and large computer resources are required in order to improve our understanding of climate and to predict reliably its change.

RESPONSES TO SPECIFIC QUESTIONS SUBMITTED TO DR. DANIEL J. DUDEK IN REGARD TO TESTIMONY BEFORE THE SENATE COMMITTEE ON ENERGY AND NATURAL REOURCES ON JUNE 23, 1988 CONCERNING CLIMATE CHANGE

1. What can U.S. farmers expect for the 90's in terms of cropping cycles as a result of global warming?

As global warming continues, the frequency of drought events such as those experienced this year will increase. These stresses will increase the variability of agricultural yields and affect farm financial recovery. Dryland operations will be particularly affected as their options to mitigate drought impacts are limited. Livestock producers dependent upon favorable feed prices and limited by the relatively longer production cycles are likely to be hardest hit by these changes. Longer term investments in conservation measures will be increasingly difficult to sustain in the face of climatic change.

Do you believe that domestic agriculture can adapt to the dramatic changes that may be in store if current warming scenarios hold true?

Agriculture as we know it will be changed. Cropping locations and intensity will adjust in response to differential regional changes. There will continue to be a substantial domestic U.S. agricultural sector and it is likely to be able to feed us, albeit at increased prices. However, the U.S. presence in world export markets may be sharply reduced as available supplies are used to satisfy domestic demands.

The regional picture is very different from the aggregate national assessment. The nation as a whole is relatively rich in agricultural resources. However, the intensity of climatic changes will vary by state and the relative profitability of agricultural enterprises will be altered in response. There is a strong possibility of large regional shifts in the location of agricultural production. Consequently, the aggregate picture does little to portray the struggles of farmers to retain land passed down through generations living under a relatively constant climate.

2. You suggest in a recent statement that long-term public investments such as water resource projects and wildlife refuges should incorporate climate change assumptions in their planning. How do you suggest the Energy and Natural Resources Committee go about achieving this goal in their own project planning?

The first imperative of a changing climate for planning is to abandon assumptions that the climate will be unchanged. While the regional uncertainties of predicted climate changes from general circulation models is still quite high, hydrologists and others dealing with inherently uncertain events have developed analytic methods to test the robustness of project designs. These sensitivity analyses may be of some assistance in decision making while the climate models are improved.

However, a more important consideration is the need to design and manage projects for flexibility. For example, much of the irrigation water in the western United States is not allocated by market processes. Rather, longterm contracts specifying fixed nontransferrable entitlements at subsidized prices are the norm. The upshot is inefficent use of the resource and substantial environmental degradation from over development and irrigation return flows. As climate changes, resources need to be able to be redeployed in response to these changes if impacts are to be mitigated. If climate change results in surface water supply reductions, water markets can efficiently reallocate supplies as well as stimulate investments in more efficient irrigation technology and mangement. More efficient water use increases the effective supply and lessens water mangement trade-offs with in-stream uses and values. Project operating rules could also be evaluated for their flexibility is responding to altered climatic conditions.

For wildlife, it is imperative that studies be undertaken to identify potential adjustment corridors to facilitate migration. However, many wildlife managers are faced with existing severe threats to the resource. Additional resources devoted to evaluating changes in critical ecosystem attributes and planning for climate change are required if existing critical efforts are not to be diluted. The priority is to include the implications of a changing climate in land acquisitions. Temperature and flow mitigation for fisheries need to be integrated into project operating rules.

3. Will increases in plant productivity as a result of higher levels of CO_2 mitigate some, or all, of the damage to agriculture as a result of climate change?

The interaction of CO_2 concentration increases and climate change stresses and their implication for crop yields is not currently well known. Existing agronomic research has focused either on the crop productivity effects of CO_2 or the impacts of climatic change. The joint implications of these simultaneous changes under field conditions have not been analyzed. Integrating each of these effects in greenhouse, chamber, and field studies is an area of priority research. Some experiments involving detailed computer simulations of plant growth processes indicate increases in some, but not all regions.

In addition, plants vary in their ability to utilize increased CO_2. Crops such as corn and sorghum exhibit much smaller productivity responses to CO_2, but high vulnerability to high temperatures and moisture stress. Further, studies emphasizing climate change effects have only used changes in mean values, i.e. changes in the underlying variability of climatic factors have not been assessed. Consequently, the increasing frequency of drought and precipitation pattern changes will still have significant impacts upon agriculture, no matter the associated productivity changes. The implication is a high degree of spatial adjustment between regions.

My own study of the implications of CO_2 and climate changes which was submitted for the record used estimates of both CO_2 and climate change effects from the existing literature. Each set of effects was analyzed separately and then combined in an economic model of U.S. agriculture adapted from the Economic Research Service of the USDA. The principal grain and commodity program crops were evaluated (barley, corn, cotton, oats, rice, sorghum, soybeans, and wheat). The following table summarizes the results of that analysis in terms of percentage changes in total U.S. crop acreage for these commodities.

Table 1. PERCENTAGE CROP ACREAGE CHANGES FROM A 1982 BASE

Crop Acreage Type	CO2 only	Climate Change Only	Combined
Dryland	-13%	+18%	+5%
Irrigated	-12%	+8%	+2%

As the table indicates, the implications for agriculture will depend significantly on the relative strength of CO_2 and climate change impacts as well as their interaction.

It is also important to note that trace gases other than CO_2 are responsible for the other 50% of the warming problem. Consequently, climatic changes equivalent to those caused by a doubling of the CO_2 concentration in the atmosphere will occur several decades before the doubling.

4. Will global warming affect dryland farming in a different manner than it will irrigated farms? If so how?

As indicated in the testimony by Dr. Manabe, precipitation pattern changes and evapotranspirational changes affect soil moisture which is critical to the success of dryland agricultural operations. His modeling results indicate the possibility of severe mid-continental summer dryness. Traditional dryland farming regions will have few alternatives in the short-run. Farmers faced with these conditions can alter crop mix or type, adopt more drought tolerant varieties, utilize soil moisture conserving practices, and invest in supplemental irrigation. No doubt, the land grant system would emphasize both genetic and agricultural practice mitigation research.

Irrigated operations may be better shielded against some of the climatic changes particularly those associated with single season droughts. However, even irrigated agriculture is not immune from climate change impacts as precipitation pattern or seasonal changes can affect basic water supplies as well. It is likely that the relative economic importance of irrigated versus dryland farming is likely to be altered with greater emphasis on both permanent and supplemental irrigation. These changes will place a new urgency on addressing the problems of nonpoint source pollution from irrigated farm operations.

Would a renewed emphasis on federally funded water projects (Bureau of Reclamation) help to alleviate reliance on irregular rainfall patterns?

Since we are facing some climate change no matter what future actions are taken to manage greenhouse gases, mitigation measures will play an important role in diminishing the ultimate impacts from climate change. One of the chief impacts of climate change may be to alter the spatial pattern of demand for resources, particularly water. It is generally expected that climate changes will shift the relative intensity of agricultural operations northward. This shift will be onto lands currently important as wildlife habitat, for example, the primary breeding regions known as the prairie potholes and parklands. Anticipatory expansion of water supply facilities would only exacerbate existing resource conflicts and increase the current environmental damage from project construction and operation.

The Bureau has been involved in some nonstructural projects which would benefit farmers faced with more variable water supplies. In the west, a technique known as scientific irrigation scheduling has been developed and applied to the problem of increasing the efficiency of increasingly scarce water supplies. This technique involves sophisticated weather instrumentation networks, computer modeling, and extensive field contact for calibration on individual fields. The expansion of such weather driven efficiency measures would be more important and cost-effective in mitigating climate change impacts than expanded dam construction.

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August 24, 1988

Honorable J. Bennett Johnston
Committee on Energy and Natural Resources
United States Senate
Washington, D.C. 20510

Dear Senator Johnston:

Enclosed are the answers to the follow-up questions submitted by members of the Energy and Natural Resources Committee.

I greatly appreciated the opportunity to participate in the greenhouse hearings and hope that my testimony and responses will be useful as you and the Committee as you address what I feel to be the greatest challenge we as a nation and a global society have ever faced.

Sincerely,

William R. Moomaw

William R. Moomaw
Director, Climate, Energy and
Pollution Program

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Responses to Senator Murkowski's Questions
Dr. William R. Moomaw

1a) Can conservation alone achieve the necessary 50 to 60 percent reductions?

If by "conservation" we mean improved efficiency in the use of fossil fuels, it is possible for the United States to reduce its fossil fuel consumption by 50 percent. I base my answer on a comparison with Western European countries which enjoy a comparable standard of living to ours, but use only half as much energy per capita as we do, and continue to produce a dollar of gross national product with half the energy we require. In fact, the only countries that utilize energy less efficiently than we do are the Soviet Union and some of its allies, especially Poland, China and a handful of developing countries.

It is important to recognize that Japan and Western Europe are energy efficient for economic reasons, which is a major factor in their international competitiveness. Never-the-less, patterns of energy use play a major role in the release of carbon dioxide. The U.S. leads all nations with 26 percent of the total followed by the Soviet Union with 21 percent, Western Europe with 17 percent, China with 11 percent, Japan with 5 percent and the developing world - 18 percent. (1985 data). By improving the efficiency of our energy use, the United States was able to expand its economy by 35 percent between 1973 and 1986 with zero increase in energy. Modest additional efficiency gains could lead to an actual decrease in energy use.

1b) Is a greater reliance on nuclear energy one of our best alternatives to dependence on fossil fuel burning?

Since nuclear power emits no carbon dioxide, it would appear to be an alternative to fossil fuels. It is important to realize that nuclear power is used solely for the production of electricity in the United States. Energy inputs into the electrical generation system amounted to 36.2 percent of our energy use in 1987. This produced usable electricity equal to 11.5 percent of total U.S. energy consumption, the other two-thirds of the total being lost as heat. Of the electricity produced, nuclear contributed 17.7 percent of the U.S. total or 2.0 percent of our end-use energy. Neverthe-less, because of our heavy use of coal to generate electricity, approximately 35 percent of U.S. carbon dioxide emissions come from utilities, just ahead of the 30 percent contribution from the transportation sector.

If all fossil fuel produced electricity in the United

States were generated by nuclear power, carbon dioxide would only be reduced by about nine percent. Replacing all existing fossil fuel generating stations in the U.S. would require a more than five-fold expansion of nuclear power. At the present time, the U.S. has 109 operational nuclear power plants, 14 construction permits granted, 2 on order and 2, Shoreham and Seabrook, on indefinite hold. The last time a new nuclear plant was announced was in 1977. It is very clear that how ever one feels about the advantages of nuclear power for offsetting the greenhouse effect, the current generation of nuclear technology will not contribute much beyond what it already has to reducing carbon dioxide emissions. It is also the case that we actually utilize relatively little electricity compared to the direct combustion of fossil fuels. We would also need a major revolution to shift our transportation system to electric powered vehicles, and a similar change in our industrial processes before we could utilize the expanded output of a nuclear society.

1c) If not nuclear, then what?

On the supply side we can improve the efficiency with which electricity is generated so that we releese less carbon dioxide for each unit of electricity produced. New aeroderivative turbines developed originally for large military and civilian aircraft promise efficiencies as high as 49 percent when using natural gas, and as high es 42 percent when using coal. These would be major improvements over current steam boiler technology with numerous clean air benefits as well. Improved cogeneration technology can also quickly make a significant contribution to net carbon releases.

A second near-term strategy over the coming decade would be to return to the mix of coal and natural gas utilized in 1973. In the past 14 years, five quads of natural gas were replaced by an equivalent amount of coal. Reversing that change would reduce carbon dioxide emissions by the same amount as expanding our nuclear power capacity by 50 percent and using this expansion to replace the equivalent amount of existing coal plants. A return to gas could be accomplished at a fraction of the cost of building new power stations of any kind.

Both of these proposals along with improved energy efficiency are of course part of a strategy for slowing the growth of carbon dioxide while we make a transition to non-carbon based fuels. As I have indicated earlier, the current generation of nuclear power plants is not likely to make a significantly greater contribution that it does at present. If nuclear power is to play a significant role, we are talking about the next generation of plants which must be designed to meet the safety, proliferation, waste disposal and, perhaps most significantly, the economic concerns which currently discourage further investment. Even if we began now, the first new generation plants could not appear for 10 years, and they would not be present in large numbers for 20. By that time we must ask that other energy sources will be available.

At the present time, solar thermal electricity looks far more promising that anyone would have imagined even a few years ago. Several commercial plants are now being constructed in California and reportedly in Israel. Costs are said to be comparable to new nuclear plants. Photovoltaic technology has also improve dramatically in price and efficiency and is now cost competitive with remote diesel generated electricity. Another promising application of photovoltaics is in the generation of hydrogen fuel.

A West German consortium consisting of Siemans, BMW and the government are building the first solar photovoltaic-hydrogen facility during the coming year. Both BMW and Mercedes have a hydrogen automobile research program and additional work is being done in the Soviet Union and to a lesser extent, in the United States. In appropriate locations, wind turbines can make a contribution (just as hydropower does) which are now becoming comparable in cost with currently constructed nuclear plants. Although limited to particular areas, geothermal power, in which the U.S. is the world leader, can also be a source of non-carbon based energy.

Finally, we must examine the role to be played by biologically based fuels. This is an area that requires close attention since burning biomass releases a relatively large amount of carbon dioxide for each BTU of energy generated (approximately 50 percent more than natural gas). Furthermore, the use of energy intensive fertilizers and cultivation techniques can lower the net energy yield still further while releasing more carbon dioxide and depleting top soil. Despite these potential problems, biofuels themselves, if grown on a sustained basis, utilize the same amount of carbon dioxide during growth that they release during combustion. To the extent they replace fossil fuels in areas such as transportation, they are likely to reduce net carbon dioxide emissions significantly.

Within the next twenty years, each of the technologies I have described should be a well-established part of our energy mix if we support their development now. Nuclear and the renewables should then be compared on the basis of their relative economic costs and environmental and social benefits.

1d) What percentage of fossil fuel reductions can we reasonably expect form the alternatives I have suggested?

It is difficult to predict market shares of emerging technologies. It does appear that if we continue to improve the efficiency with which we continue to use energy, and introduce the technologies and fuel switches I have described, the U.S. could reduce carbon dioxide levels by at least 25 percent during the next 20 years. Retiring older, less efficient coal plants in particular and replacing them with modern gas turbines, cogeneration and renewables will be the most effective method for introducing these technologies. Instead we have policies which extend the life of existing plants thereby locking us into low efficiency, high pollution an carbon dioxide emitting facilities.

2. To what extent does fossil fuel use by aircraft contribute to excessive carbon dioxide or ozone depletion?

a) This is a very interesting question.

Aircraft contribute a relatively small fraction of carbon dioxide to the atmosphere. The fact that they deliver it high in the atmosphere makes little difference in overall global warming. Releasing carbon dioxide at higher altitudes does marginally alter the distribution of this gas in the atmosphere and could lead to some slight additional cooling in the stratosphere. Ordinary aircraft have only a very small possibility of depleting stratospheric ozone.

b) Are there valid scientific reasons for limiting the development of supersonic or hypersonic aircraft?

Since both hypersonic and supersonic aircraft fly at higher altitudes that reach into the stratosphere, one should examine their role very closely. Both of these types of aircraft have the potential for releasing nitrogen oxides which have the capability for depleting ozone, but some of which can also tie up ozone depleting chlorine. Careful analysis of the specific characteristics of the exhaust needs to be done to assess the overall impact on ozone depletion. Of more serious concern is the addition of water vapor from the exhaust of these aircraft to the stratosphere. It was recently found that polar stratospheric clouds play a crucial role in the dramatic appearance of the Antarctic ozone hole. Adding more water vapor to the stratosphere could permit such ice crystal clouds to form at higher temperatures than those currently found mostly over the south polar region. This could lead to much greater ozone loss over the arctic and perhaps elsewhere in the atmosphere.

It is also important to recognize that such high speed aircraft consume enormous amounts of fuel per passenger mile and, if the Concord experience is any indication, involve heavy developmental and operating subsidies.

3. If I sat on the appropriations committee..., what areas would I fund?

My first priority would be to fund energy efficiency programs that can be implemented immediately. I would start with projects within the federal government in building and auto fleet efficiency, and then make grants to the states to make their operations more efficient as well. Then I would utilize federal purchasing power to create markets for solar and other renewable technologies to hasten their development. I would also support research and development in the fields of production and end-use efficiency, solar, hydrogen and other renewables and explore a new generation of nuclear power. Because nuclear research tends to be so expensive, care must be taken to insure that it does not preempt all of the other areas.

Funding of new innovative projects by utilities, schools, hospitals, industries and other parts of the private sectors. There should also be support for a long-term (at least 10 years) scientific study and monitoring program in global climate change. This program should also provide training for young scientists. Policy research should also by supported. Funds should be made available for both our bilateral and multilateral foreign aid and loan programs to develop energy efficient and renewable energy technologies.

Other options that lie outside of the appropriations process include establishing a carbon tax to discourage the use of fossil fuels, encourage non-carbon based energy sources, and raise revenue to finance the transition to new energy supplies. One might also wish to examine policies that would enhance automobile efficiency and household, commercial and industrial efficiencies. One suggestion is to require specified levels of energy efficiency in order to qualify homes for a VA or FHA loan.

Answers to specific questions directed to William R. Moomaw

1. Do you believe that the nation, and in fact the world, are mobilizing sufficient economic, scientific, and political resources to properly address the ramifications of global warming? If not, what steps must be taken?

No. Despite the fact that global warming from increased burning of fossil fuels was first described quantitatively 92 years ago by S. Arrhenius, we have just begun to realize the full implications of global warming for society. While there are many details of global warming that need to be clarified, I believe that there is sufficient certainty over its direction and extent that we must begin the transition to a less carbon intensive society.

This transition must be guided by up-to-date science and sound policy analysis. While energy use is directly and indirectly responsible for the bulk of global warming, finding the sources of methane and nitrous oxide, gaining a better understanding of ocean-atmospheric interactions and measuring the role of plants in the carbon cycle require further research. I propose that we commit ourselves to a ten to thirty year scientific research program into global earth and ecological sciences that will guide our policy as it evolves over the coming year. As the stratospheric ozone hole has demonstrated, there are likely to be surprises in the operation of planetary systems, so we must fund a broad range of investigations and train and support new scientists in appropriate fields. We must also support policy research, based upon scientific knowledge, that will guide us along the least economically costly and most effective transition path.

We should begin that transition by implementing rapidly those policies that are least disruptive to society, but which provide large multiple benefits. First on our list of priorities should be improved energy efficiency. Since the transportation sector releases 30 percent and the electric utility sector 35 percent of U.S. CO_2 these are prime targets for reduction. Second, a rapid phasing out of CFCs could readily be accomplished during the next decade. Third, a shift away from coal toward natural gas could also be accomplished in to near future. Simultaneously we should begin the transition to carbonless fuels that must be in place within the next 20 years. This will require major research, development and marketplace testing of solar thermal, solar photovoltaic, other renewables including hydrogen production, and an examination of the nuclear option. The latter will have to be far more economical and safe than current power plants to become acceptable.

2. What has been done in the policy realm to directly quantify the economic costs to the United States should a global warming take place? Are we able to assign numbers to the possible disruptions to trade, agriculture, commerce, etc. as a result of global warming?

The quantitative analysis of the costs of the greenhouse effect are just beginning. Studies have been done on the cost of sea level rise on Charleston, South Carolina and Galveston, Texas, for example. One can extrapolate costs of dike building in the Netherlands and temporary measures taken along the Great Lakes and Great Salt Lake. One can utilize the costs of this year's drought to estimate the overall cost to crops, navigation and power generation. The Bellagio report suggests that mitigation costs might lie in the range of several hundred billion dollars by 2030. More work needs to be done, and some is currently underway.

3. If you were to draft a bill outlining three Greenhouse gas reduction policies what would they be in order of importance?

The first would be to introduce energy efficiency into the society. This would begin with the federal government, extend to the States and move to the private sector through improved auto efficiency, building and lighting standards. We can learn a great deal by examining effective and ineffective policies introduced in the United States and abroad during the 1970s. One option that should be seriously considered is a carbon tax that would raise the price of fossil fuels enough to encourage their efficient use.

The second area that would reduce warming significantly would be to phase out CFCs completely during the next decade. Use specific regulations could be imposed to reduce pure waste and non-essential uses such as the approximately 19 percent of total CFC release that comes from leaking automobile air conditioners each year. Other policies should place a fee on CFCs to encourage their recycling and early replacement by alternatives.

The third policy that could be implemented rapidly would be fuel switching from coal to natural gas. A return to the power generation fuel mix of 1973 would reduce carbon dioxide emissions by as much as a 50 percent expansion of our nuclear capacity as a replacement for coal. Such a fuel switch would be far less expensive.

These three strategies are clearly transition policies. For the long run we must develop a carbonless energy policy which relies on solar, renewables and possibly a new, safe, cost effective generation of nuclear power.

APPENDIX II

ALTERNATIVES TO COAL COMBUSTION*

Leon Green, Jr.
Washington, DC

Abstract. The degree of climatic warming due to buildup of CO_2 in the atmosphere may be mitigated by using coal not as fuel but as feedstock for allothermal gasification by exogenous heat at large centralized facilities, and controlling the use of the CO_2 thereby produced to sequester it or recycle most of it into the biosphere. The CO_2 and NH_3 produced in such a control system would constitute basic inputs for agricultural or industrial uses at widely distributed locations. In particular, they would serve as nutrients for intensive cultivation of biomass which would provide locally produced food, fiber and fuel, or locally generated heat and power. The central systems could also produce methanol or hydrocarbons as required for other industrial or utility power and for transportation fuels. High-temperature nuclear process heat technology has been developed in Germany to the point of readiness for demonstration of coal gasification. Completion of this program is essential if the technology is to be ready for deployment when the need for positive action to mitigate global warming is recognized as critical.

1. Introduction

> It is clear that the greenhouse effect and climate change are real concerns for the condition of the planet within our lifetime (Mitchell, 1987).

Having ignored earlier warnings of the need for active measures to prevent global warming due to buildup of carbon dioxide in the atmosphere (e.g., Schneider, 1978: Laurmann, 1979), the world now finds itself facing an inevitable further warming of uncertain degree. It has been estimated that, even if all CO_2 emissions were to cease today, there is already enought CO_2 accumulated in the atmosphere to produce an average surface temperature rise of 0.5-1.5 C after equilibration of the oceans in temperature. The greenhouse effect is now the subject of active investigation by

*Adapted from the introduction to the symposium "Prospects for Mitigating Climatic Warming by Carbon Dioxide Control" at the Annual Meeting of the American Association for the Advancement of Science, Boston, Massachusetts, February 12, 1988.

the international scientific community, and summaries of our current knowledge of the suject have recently been published (Farrell, 1987; Edmonds, et al., 1987).

2. Possible Mitigation Strategies

Few of the studies conducted early in this period of increased international activity considered the possible effects of deliberate human efforts toward mitigation of the warming trend. One study by the National Academy of Sciences advised that near-term preventive action would be premature and could better await the findings of ongoing research (NAS, 1983). Even the potential contributions of yet unknown technologies have been discounted: "The single largest contributor to future climate change is carbon dioxide; no foreseeable technology can deal with the vast quantities and distributed sources of that essential by-product of the burning of coal, oil and natural gas" (MacDonald, 1985). Such a pessimistic conclusion has been challenged more recently in a study which compared the rates of CO_2 buildup estimated according to different policy scenarios but which again warned that "...unless policies are implemented soon to limit greenhouse gas emissions, intolerable levels of global warming will result" (Mintzer, 1987).

Since the combustion of fossil fuels is the major source of CO_2 emissions, constraint on the use of such fuels, particularly coal, is an obvious measure for limiting these emissions (Rotty and Weinberg, 1977). Another approach is to recycle carbon from the atmosphere into the biosphere by global reforestation (Dyson, 1977; Dyson and Marland, 1979; Marland, 1988). However, capturing the low concentration of CO_2 in the normal atmosphere by forestation is a slow process (but one nevertheless well worth initiating), and coal is far too important a resource to be abnegated.

Scrubbing CO_2 from the flue gas of coal-fired power plants is technically feasible but, except for special applications, not economically practical (Steinberg, 1983). Improvements in the efficiency of end-use energy technologies (Goldemberg, _et al._, 1985, 1987; Cheng, _et al._, 1986) is an obviously desirable approach, but one which, like growing trees, requires a long time for its effect to be manifested. The substitution of nuclear power for coal-based central station power is an option now subject to a _de facto_ moratorium for reasons which need not be belabored here, and which in any event does not address the problems of emissions from industrial power and process plants or from use of transportation fuels.

A complementary approach to limiting CO_2 emissions could be to utilize nuclear energy in the form of high-temperature process heat for the gasification of coal or the reforming of hydrocarbons and to capture the CO_2 thus produced in concentrated form by scrubbing the process stream (Green, 1967, 1968). Some could then be sequestered in the hydrosphere (Marchetti, 1977) or in stable chemical compounds, but most of it recycled into the biosphere by photosynthesis under controlled conditions (Green, _op. cit._). Such an approach would exploit our combined fossil, solar and nuclear energy resources in an environmentally benign manner.

3. Nuclear Process Heat

That heat delivered to a chemical process "...can be worth several times as much as if it were merely supplied to a heat engine to generate electricity" was emphasized in 1947 by John J. Grebe of the Dow Chemical Company, who argued that such an application of high-temperature nuclear heat would be "...economically more attractive than more-or-less marginal competition with coal for power production" (Nordheim, 1947). Two decades later a respected economist observed that "..the real economic potential of nuclear fuel is no more captured in its substitution for fossil fuels in large-scale electric power stations...than was the economic potential of petroleum realized when kerosene replaced whale oil in lamps used in the home" (Schurr, 1968). Despite the importance of these cited and other similar perceptions, process applications of nuclear energy never enjoyed the same priority as power in the development programs of the U.S. Atomic Energy Commission (Green and Anderson, 1974) or its successors, the Energy Research and Development Administration and Department of Energy. Such applications have received only token support during the past several years, and the effort is now dormant.

Fortunately, development of process heat applications of the high-temperature reactor have proceeded abroad, in Japan, the USSR, and especially in the Federal Republic of Germany, where the principal application investigated has been the gasification of coal (van Heek, et. al., 1982), sometimes in combination with other processes (e.g., Barnert, et. al., 1984; Barnert, 1986). Although the details of the of the FRG program are beyond the scope of this paper, it may be stated in brief that the principal development problem involved has been materials of construction for helium heat exchangers immersed in fluidized-bed gasifiers, design of which can also be improved. The upper operational temperature limit of metallic materials has been established to be 950 C, sufficient for present processes. However, even the FRG process heat development is now jeopardized by budget stringency (Klusman and Specks, 1986) and public funding for the ongoing program at KFA Julich is assured only through 1988. This problem is compounded by the recent drop in the price of oil and coal, which has temporarily eliminated the economic advantage of fission heat vs. conventional fossil heat (Schulten, 1985), thus rendering nuclear gasification a long-term objective from a purely economic point of view (Specks, 1987) toward which the KFA Julich program is now directed (Barnert, 1987). Accordingly, the environmental desirability of nuclear process heat (Green, 1981) now constitutes the strongest rationale for its application to allothermal gasification technology and its essential role in CO_2 control as outlined below.

4. Carbon Dioxide Control System

Use of exogenous heat to replace the heat generated by coal combustion in conventional "autothermal" gasification eliminates the carbon dioxide generated by combustion for which synfuel projects have been criticized (e.g., MacDonald, 1987) and leaves only that produced by the shift reaction in the indirectly-heated "allothermal" gasifier. Since the gasifier operates at high pressure (about 40 bars) and the process stream is undiluted by nitrogen, the CO_2 is concentrated and can be scrubbed from the stream much more efficiently than would be the case in scrubbing the dilute stack gas of a coal-fired power plant.

The gasification and shift steps constitute the first stage of the CO_2 control system diagrammed in Figure 1. As indicated therein, a major alternative option is not to shift the mixture of CO and H_2 from the water-gas reaction to CO_2 and more H_2, but to use it as synthesis gas for producing methane, methanol and other organic compounds as suggested in Figures 2 and 3. This "syngas option" has been studied (Häfele, et. al., 1986) in a system which transfers the burden of heat and power generation heavily from coal to methanol, thus postponing the combustion of it and other products until the stage of their final use (Kaya, 1986). Although this system is billed as one of "zero emissions" of CO_2, it may be described more accurately as one with reduced and delayed emissions.

By contrast, the system outlined in Figure 1 can indeed approximate a "zero emissions" system since, in principle, all the CO_2 produced can be sequestered or recycled into the biosphere. To establish the optimum economic vs. climatic balance among the multiple options offered by the systems of Figures 1 and 2 will require quantification of mass flows by a systems analysis for which many of the data required are not yet available. However, it may be surmised *a priori* that a full transition to carbonless fuels over the next century as recently proposed by Häfele (see Barker, 1986) is neither practical nor desirable.

Hydrocarbons, alcohols and other organic compounds (cf. Figure 3) are simply too useful for too many human purposes to be abjured.

In the system for effecting maximum carbon recycle (Figure 1) all the intermediate synthesis gas is shifted to CO_2 and H_2. Ammonia is selected as the hydrogen energy carrier because of its many uses as a basic agricultural and industrial chemical and major article of world-wide commerce which is routinely transported ported by truck, tank car, barge and ship, and which, like CO_2, can also be economically transmitted over long distances in liquid form via pipeline (Green, 1980). For agricultural purposes ammonia can be converted into solid or liquid fertilizer, dissolved in irrigation water or injected directly into the soil. It is also a clean-burning fuel whose use has been demonstrated in piston engines and combustion turbines (Gray, et. al., 1966; Pratt and Starkman, 1967).

For simplicity, Figure 1 indicates only one feedstock application of ammonia: conversion into urea, another compound with many industrial and agricultural uses including a synthetic feed supplement for ruminant livestock (Virtanen, 1966; Byerly, 1967). This application also illustrates one of the multiple routes by which CO_2 can be sequestered in solid form (Steinberg, op. cit.).

At this point it is worth digressing to note that the use of urea as a form of aid to developing countries might alleviate the counterproductive effect of providing food directly, which discourages domestic agriculture and induces movement of farmers off the land and into overcrowded urban centers. Providing instead a fertilizer which can also serve as a feed supplement could let the farmers conserve for sale some of their crop otherwise diverted to fodder and thereby induce them to remain productively engaged in agriculture. The present paper, however, deals with biomass technologies applicable primarily by industrialized countries which are the greatest CO_2 emitters.

5. Solar Energy Input

Aside from the oceans, the recycling of carbon dioxide into the biosphere by photosynthesis constitutes the highest-capacity nonatmospheric "sink" for CO_2 potentially available. Because of the immense amount of energy captured annually by photosynthesis ("God's way" of converting thermonuclear energy) this use of CO_2 to increase the photosynthetic efficiency of plants is also the most beneficial in that it provides a means for introducing a very large-scale input of solar energy into the total system.

This objective may be accomplished by diverting massive flows of chemical energy from the large, centralized gasification complex (cf. Figure 1 left) to smaller, dispersed operations (Figure 1 right) which convert the biomass grown thereby into locally produced food, fiber and fuel or into locally generated heat and power. It may thus be seen that the system outlined in Figure 1 contains both "hard" and "soft" energy paths (Lovins, 1976, 1977) and achieves wide distribution of local sites for energy conversion and use.

From the viewpoint of mitigating the greenhouse effect it might seem desirable to maximize the solar energy input to satisfy local heat and power needs by means of the "soft" biomass cycle (with its "hard" nutrient inputs). On the other hand, the greater the fraction of biomass converted to energy rather than used to sequester carbon (as wood in lumber products, standing forests or peat bogs), the more CO_2 nutrient is released into the atmosphere. The optimum balance is not obvious a priori but will require further analysis.

6. Biomass Technologies

The dual objectives of biomass technology development are to produce biomass more efficiently and to use it more efficiently than is now practiced. Except for the low photosynthetic efficiency of its growth, biomass conversion is by far the most efficient route for utilization of solar energy (Zracket and Scholl, 1980). Improved production is thus both the more important objective and the one to which nurturing by selective application of carbon dioxide can contribute.

Wood is man's original fuel, and the technology for its use has evolved continuously over the ages. Forestry research activities sponsored by the International Energy Agency biomass program include investigation of the effect of nutrients on growth, but not that of carbon dioxide because CO_2 is not conventionally considered a variable which affects tree growth. This traditional attitude must change.

There are obvious engineering problems which must be solved in order to apply the desired CO_2 amendment to forests. As the trees grow taller, the more difficult it becomes for a CO_2-rich environment to be economically maintained (Allen, et. al., 1985) even in "conventional" short-rotation forestry. To realize CO_2-nurtured growth outside of a greenhouse environment, trees may require frequent coppicing of dense plantings to produce "wood grass" with controlled micrometeorology of the canopied space by careful "agro-aerodynamic" methods (Lemon, 1967). Alternatively, CO_2 nurturing of seedlings in greenhouses with artificial illumination can shorten the time required for early growth prior to outplantation (Hanover, 1976).

It should be noted here that intensive cultivation of energy crops by developed countries need not compete with food crops for limited land resources; most such countries have agricultural surpluses. Marginal land now devoted to needlessly subsidized agriculture might well be better utilized for energy crops, especially if it requires irrigation.

On much otherwise arid land (in, say, the U.S. southwest), carefully controlled application of water by efficient "drip" irrigation methods could exploit the known behavior of plant species to respond strongly to CO_2 nurturing under conditions of stress due to water limitation (Bjorkman, et. al., 1983). An energy crop (say, coppiced eucalyptus) would normally require less water than would most food crops, and the CO_2 amendment would increase its efficiency of water usage still further.

Given sufficient water, the ultimate factor limiting the output of plant culture is the photosynthetic efficiency of the crop (Brown, 1967), and under conditions of intense insolation the rate of growth of high-yielding crops is limited by the availability of CO_2 (Lemon, et al., 1963). This limitation might be removed by using a "drip" irrigation system to provide water at night and carbon dioxide by day.

Wood, of course, is the energy crop most difficult to nurture by CO_2 enrichment for the reason noted above, and other food and fiber crops are more amenable. A wide program of research on plant responses to increased carbon dioxide levels initiated by the U.S. Departments of Agriculture and of Energy (see Allen, 1986) emphasizes major food crops such as soybeans (e.g., Hrubec, et. al., 1985; Allen, et. al., 1987), the response of which is shown in Figure 4. Other crops showing good response include cotton and spinach, as well as aquatic weeds (Spencer and Bowes, 1986). The possible use of fiber crops cotton and kenaf (Dempsey, 1975) as CO_2-nurtured energy crops deserves evaluation.

Another possibly fruitful area of investigation may be intensive cultivation of algae, for example the filamentous blue-green Lyngbya (Beer, et. al., 1986), or spirulina, an efficient protein producer which has been collected and eaten by central African tribes since ancient times and is now cultivated as a trendy "health food" in California. A long-range program now being conducted by the Biomass Technology Division of the U.S. Department of Energy is aimed at production of microalgae which when stressed directly fix lipids, potentially direct substitutes for diesel fuels, and the cell growth of such algae requires large quantities of CO_2 (Walter, 1987). Biomass growth is not the author's field, however, and must be addressed by others.

Biomass utilization, on the other hand, is a more familiar subject. The production of ethanol, oil and other products from corn is a long-established, large-scale commercial technology which needs no elaboration here. In the U.S. midwest ethanol is now blended with gasoline for enhancement of octane ratings, and it is burned "neat" as motor fuel in Brazil. Its use in combustion turbines, like that of methanol, would be straightforward.

Whereas use of fuelwood is ancient, direct combustion of solid biomass in large installations for industrial and small utility generation of heat and electric power is a more recent application, but one which is rapidly spreading in both industrialized and less-developed countries. The key to this rapid development is the commercial availability of the "circulating" fluidized-bed combustor (e.g., Schwieger, 1985; Makansi and Schwieger, 1987; Smock, 1987), which is capable of operating efficiently on a wide range of high-moisture or low-grade fuels including wood and wood waste, peat, rice hulls, cotton-seed hulls, bagasse, straw, cattle manure and sewage sludge. Present wood-burning CFBC boiler installations tend to be in the size range of 10-50 megawatts (electric), but the upper limit is set by the radius of economical fuel gathering, not by the conversion technology.

Wood and other biomass can also be thermally gasified by fluidized-bed techniques to produce low-Btu fuel gas or synthesis gas using commercial technology, but such gasifiers are generally restricted to special locations where they are competitive with natural gas. The largest wood gasification plant reported to date (Makansi, 1987) produces low-Btu gas at a net rate of about 200 million Btu (ca. 200 billion Joules) per hour for process heat, or equivalent to a potential power output of about 20 MW(e). Research on biological gasification and liquefaction techniques for biomass is also underway, but such methods have not yet been developed to practical status.

In the long run, biomass gasification and liquefaction technologies will have to be economically competitive with their equivalent coal technologies discussed earlier. Since the latter will enjoy economies of large scale, this may prove too high a hurdle except in special situations. On the other hand, present commercially-proven biomass conversion technologies such as direct combustion and fermentation/distillation will continue to be utilized for the foreseeable future. Coal-fired power plants employing circulating FBC boilers now exceed 100 MW(e) in size, and biomass-fired plants approaching that size may be anticipated if improved fuel gathering techniques are developed.

7. Time Phasing of New Energy Systems

The history of energy systems reveals that a period of about 50 years is required for market penetration of a new technology (Marchetti, 1975), and it was noted a decade ago that this rule indicates "...an immediate need to implement a revised energy policy if major climatic changes induced by increased amounts of carbon dioxide are to be avoided in the next century" (Laurmann, 1979). Estimates of the date by which atmospheric CO_2 will have doubled vary, but a rough mean is about 2050. To achieve significant deployment by that time, a new, low-emission energy technology must therefore be commercially available by the year 2000. The additional warming effect of other greenhouse gases (Wuebbles and Edmonds, 1988) makes this timing even more critical (Mintzer, op. cit.; Laurmann, 1987).

It was mentioned earlier that the development of nuclear process heat technology, an essential element in the CO_2 control system proposed here, has progressed in the Federal Republic of Germany to the point where demonstration of allothermal coal gasification is the next step. However, it was also noted that such demonstration is being jeopardized by efforts to justify such a step on economic grounds alone. Such a critical development must be justified more convincingly as one whose frúition is not merely desirable but is a bona fide climatic imperative.

Recognition of this fact will come slowly, since public perception of dangers from nuclear reactors is indeed real, whether justified or not (MacDonald, 1985). Public confidence in technology "...means that people on Main Street must think it safe..." (Markey. 1986) and thus requires introduction of new, intrinsically safe reactors (Beyea, 1986). Nevertheless, despite advocacy by some of abandoning nuclear energy (e.g., Flavin, 1987), this recognition will come surely as the fact that the consequences of unmitigated climatic warming constitute "slow catastrophe" (Lemon, 1983) permeates the public consciousness.

8. Conclusion

The foregoing discussion has envisioned a combination of fossil, nuclear and solar sources into a sustainable energy system capable of controlling net carbon dioxide emissions to the degree required for mitigation of climatic warming. With two notable exceptions, the various technologies required for this system are already available. Still missing at the "front end" of the system is the demonstration of allothermal coal gasification using high-temperature nuclear heat, but the necessary elements of the technology are at hand in the Federal Republic of Germany. Such a development must proceed under high priority if the process is to be commercially available by the time when the need for its wide and rapid application is recognized as critical for the performance of the required "geohygiene" (Sakharov, 1968).

At the "output end" of the system, further research is needed to establish the degree of enhancement of biomass growth achievable by selective CO_2 enrichment of the local environment of energy crops, to identify which plant species have the best energy potential and are most responsive to CO_2 nurturing, and to develop techniques for realizing such locally-enriched environments in practical open-air situations. Commercial technologies for converting biomass into fuel, heat and power already exist but can be improved.

The major global CO_2 emitters which will need most to initiate such "geohygienic" practices are the United States and other OECD countries, the Soviet-bloc countries, and China, which is now on the threshold of an intensive, coal-powered economic development effort. All are fully capable of deploying the technologies involved, but sufficiently rapid deployment will require prompt, deliberate national policy decisions. Such a development will not occur under a "business as usual" scenario determined by market forces in lieu of policy, since market mechanisms cannot take the place of government action (Weiss, 1987). Introduction of the alternative energy technology needed will require "strategic investments" based upon a (currently) noneconomic criterion analogous to investments in national security (Schneider, 1987) which, in fact, they will be.

It is interesting to note in closing that the carbon dioxide control system outlined above is compatible with a trend away from direct coal combustion already discernible in the U.S. electric utility industry. No new large, coal-fired power stations are being ordered. Instead, some utilities are tending to add new generating capacity in small increments in the form of combined-cycle plants "topped" by combustion turbines burning natural gas, with the option of installing local, dedicated (autothermal) coal gasification facilities later _if_ these small gasifiers become economically competitive. Such gas turbines could operate equally well on low-Btu synthesis gas, substitute natural gas (SNG) or methanol produced at large, centralized complexes by allothermal gasification, or on ethanol or syngas produced in smaller, local distilleries or biomass gasifiers.

Other utilities are adding no new generating capacity of their own, but are purchasing power from independent cogenerators or small power producers employing gas-fired combustion turbines or circulating fluid-bed boilers fired by a variety of low-cost solid fuels, including wood and wood waste. This trend will continue as the current restructuring of the electric utility industry proceeds, and presents an opportunity for introducing new, low-emission energy technologies which should not be lost.

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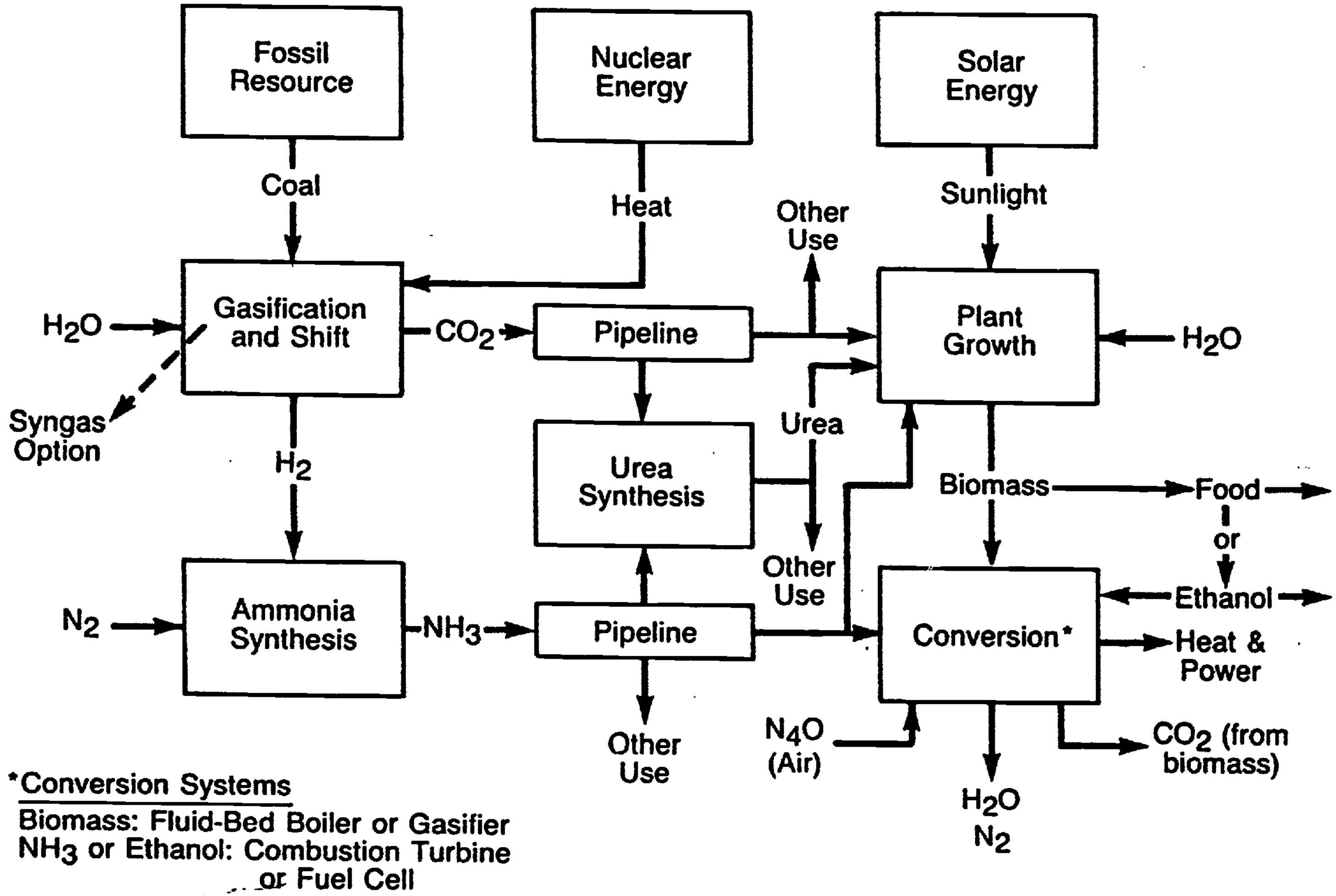
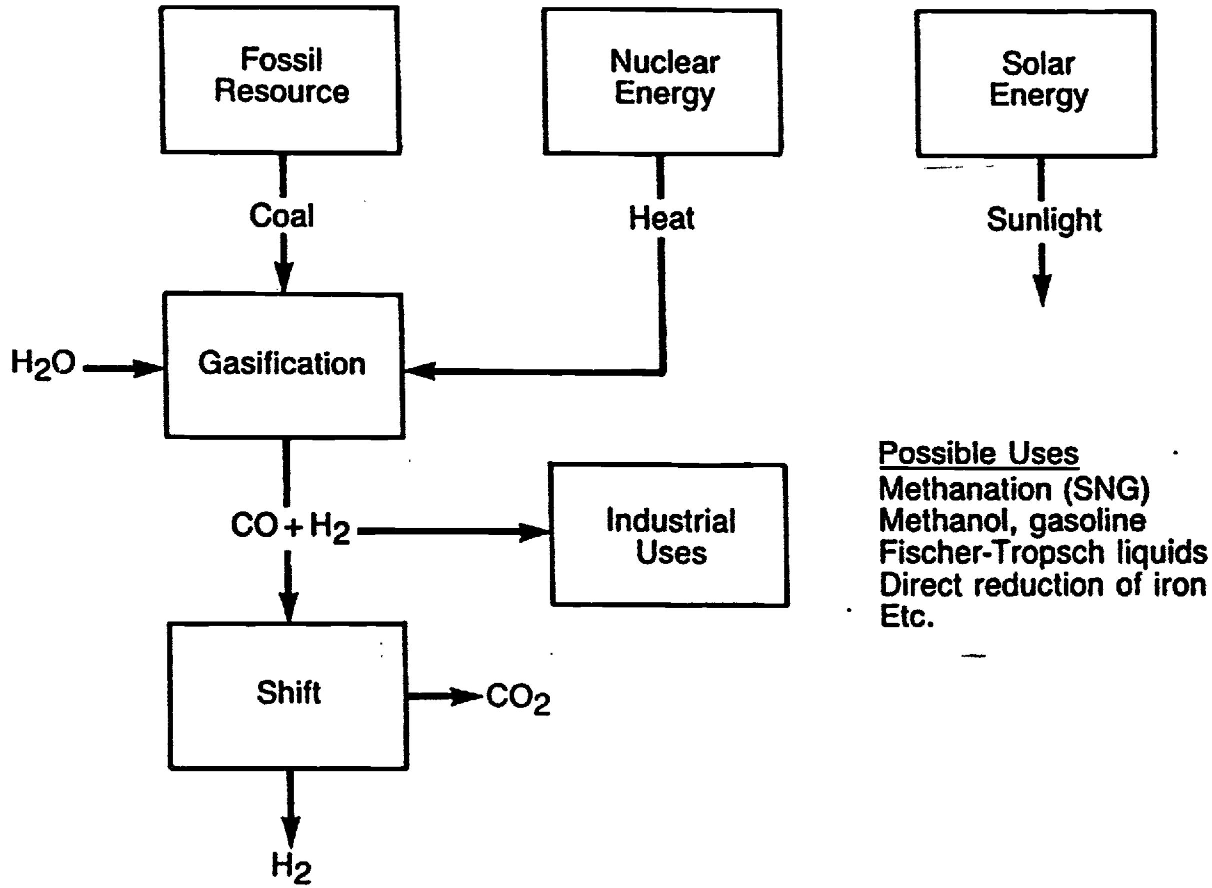
Fig. 1. System for Utilizing Fossil, Nuclear and Solar Energy Resources with Maximum Recycle of Carbon (Simplified)

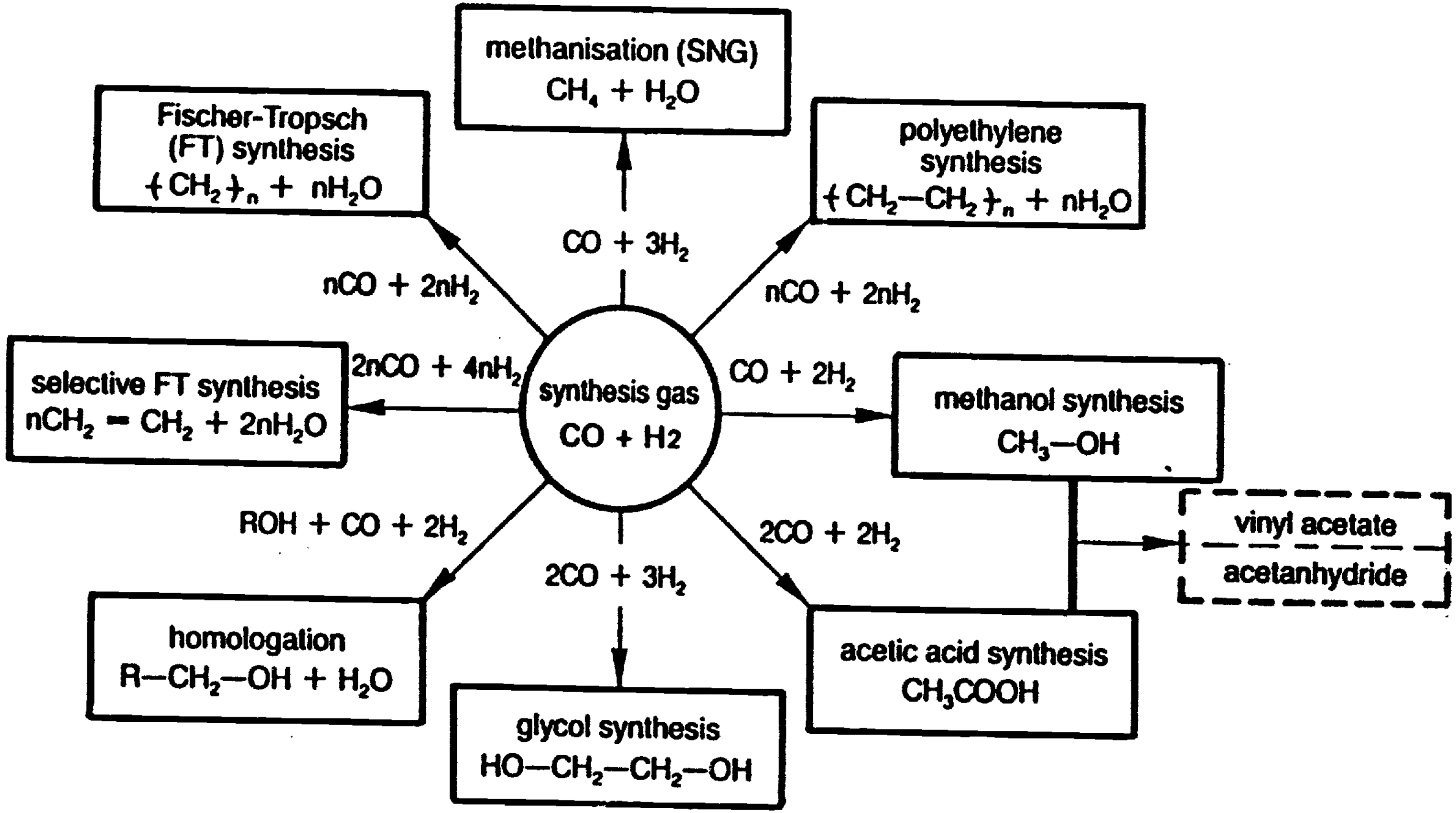
Fig. 2. Variation of System Utilizing Synthesis-Gas Option

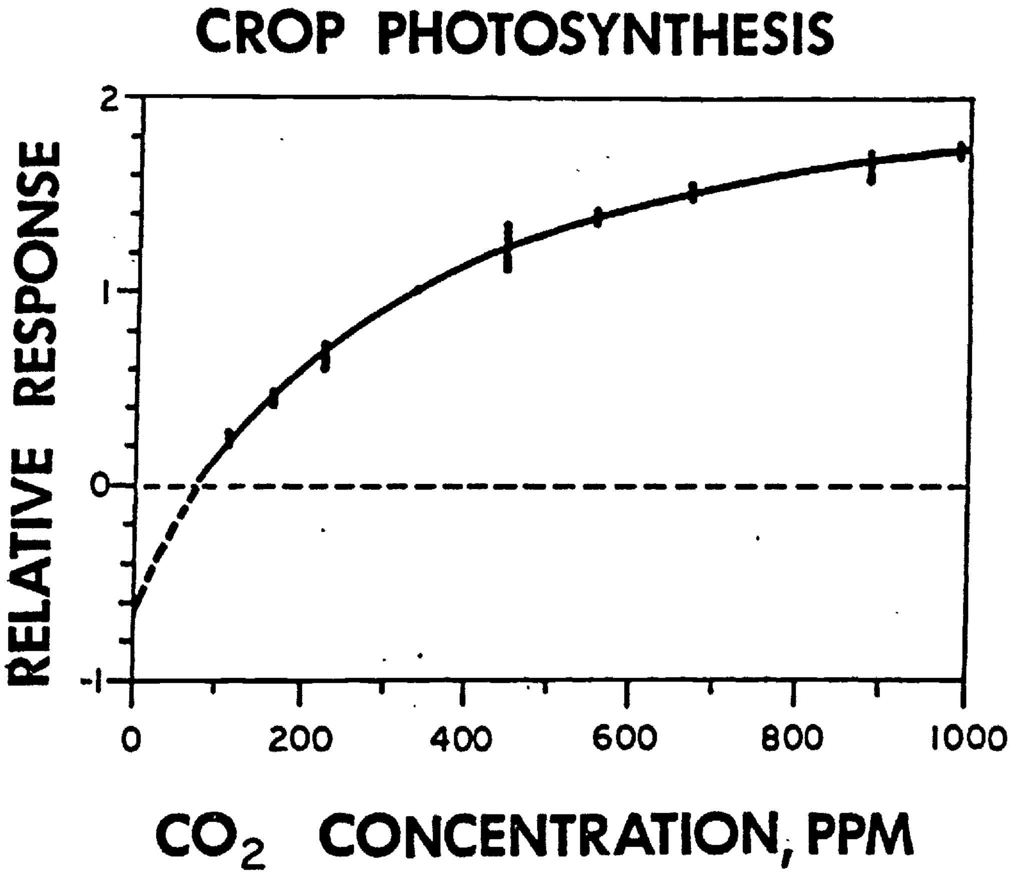
Fig. 3. Possible Products of Synthesis Gas Chemistry (courtesy of K. Knizia)

Fig. 4. Mid-day Net Photosynthesis Rate Response of Soybean Crop Canopy to CO_2 Concentration, Normalized to 330 ppm (from Allen, et. al., 1987)


Fossil Resource
Nuclear Energy
Solar Energy
Coal
Heat
Sunlight
Other Use
Gasification and Shift
H_2O
CO_2
Pipeline
Plant Growth
H_2O
Syngas Option
H_2
Urea
Urea Synthesis
Biomass
Food
or
Other Use
Ethanol
N_2
Ammonia Synthesis
NH_3
Pipeline
Conversion*
Heat & Power
Other Use
N_4O (Air)
CO_2 (from biomass)
H_2O
N_2
*Conversion Systems
Biomass: Fluid-Bed Boiler or Gasifier
NH_3 or Ethanol: Combustion Turbine or Fuel Cell


Fossil Resource
Nuclear Energy
Solar Energy
Coal
Heat
Sunlight
H_2O
Gasification
$CO + H_2$
Industrial Uses
Shift
CO_2
H_2
Possible Uses
Methanation (SNG)
Methanol, gasoline
Fischer-Tropsch liquids
Direct reduction of iron
Etc.


methanisation (SNG)
$CH_4 + H_2O$
Fischer-Tropsch
(FT) synthesis
$(CH_2)_n + nH_2O$
polyethylene
synthesis
$(CH_2-CH_2)_n + nH_2O$
$CO + 3H_2$
$nCO + 2nH_2$
$nCO + 2nH_2$
selective FT synthesis
$nCH_2 = CH_2 + 2nH_2O$
$2nCO + 4nH_2$
synthesis gas
CO + H2
$CO + 2H_2$
methanol synthesis
CH_3-OH
vinyl acetate
acetanhydride
$ROH + CO + 2H_2$
$2CO + 3H_2$
$2CO + 2H_2$
homologation
$R-CH_2-OH + H_2O$
glycol synthesis
$HO-CH_2-CH_2-OH$
acetic acid synthesis
CH_3COOH


CROP PHOTOSYNTHESIS
RELATIVE RESPONSE
2
1
0
-1
0
200
400
600
800
1000
CO2 CONCENTRATION, PPM

O