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Report to the Chairman, Environment, Energy, and Natural Resources Subcommittee, Committee on Government Operations, House of Representatives

September 1990

GLOBAL WARMING

Emission Reductions Possible as Scientific Uncertainties Are Resolved

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Resources, Community, and
Economic Development Division

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The Honorable Mike Synar
Chairman, Environment, Energy, and
Natural Resources Subcommittee,
Committee on Government Operations
House of Representatives

Dear Mr. Chairman:

This report provides an overview of federal research on global warming and identifies policy issues for dealing with climate change. It is intended to provide a framework for understanding the science and policy issues concerning global climate change.

As agreed, unless you publicly release its contents earlier, we will make no further distribution of this report until 30 days from the date of this letter. At that time, we will send copies to the Administrator of EPA, Members of Congress, and other interested parties. We will make copies available to others upon request. If you have any questions about the report, please call Richard L. Hembra, Director, Environmental Protection Issues, at (202) 275-6111. Other major contributors are listed in appendix V.

Sincerely yours,

J. Dexter Peach
Assistant Comptroller General

Executive Summary

Purpose

Growth in industry, agriculture, and transportation over the last several centuries has resulted in the increase in "greenhouse" gases, which may produce long-term and perhaps dramatic changes in global climate. The results of this increase may be higher sea levels and changes in agricultural productivity and in ecosystems.

In response to a request by the Chairman, Environment, Energy, and Natural Resources Subcommittee, House Committee on Government Operations, this report

- describes what is known and not known about greenhouse gases,
- examines the strengths and limitations of estimates of enhanced global warming, and
- identifies possible policy responses.

Background

Gases, such as carbon dioxide, methane, chlorofluorocarbons (CFCs), and nitrous oxide are building in the atmosphere, where they trap heat and cause the earth to warm. This phenomenon is enhancing the natural greenhouse effect that maintains the earth's current average temperature at about 60 degrees Fahrenheit.

To understand the effect of increases in greenhouse gases, scientists use complex computer models, known as general circulation models, to analyze future climate changes. Four federal agencies operate or fund such models: the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the National Science Foundation (NSF). Additional research on global climate change is conducted primarily by these agencies and the U.S. Department of Agriculture, the Environmental Protection Agency (EPA), and the U.S. Geological Survey. Funding devoted primarily to research in climate change by these seven agencies was over $660 million in fiscal year 1990. The administration's budget for fiscal year 1991 proposed increasing funding to over $1 billion.

Results in Brief

Industrial and agricultural activities are causing the atmospheric concentrations of some greenhouse gases to exceed historic levels. Without action now, these concentrations are expected to grow, although the rate of increase is uncertain. From their review of computer modeling results, most climate scientists agree that the climate's response to this growth will be an increased average temperature over the next 100 years. They do not concur, however, on the timing and magnitude of this change or on the associated regional climate changes.

While research should reduce these scientific uncertainties, quick fixes or easy answers are unlikely to emerge. Rather, research results are expected to continue pointing to the need for a comprehensive multinational, multidecade response strategy. In the meantime, however, many agree that certain actions can be justified because they have benefits in addition to reducing greenhouse gases. Reducing CFCs is an example of one such activity already underway, and more can be done in other areas, such as improving energy efficiency.

Principal Findings

Causes of Global Warming

Concentrations of greenhouse gases are increasing primarily because of fossil fuel combustion and the use of nitrogen fertilizers and CFCs. Greenhouse gases are expected to increase because of these activities, although at an uncertain rate.

Carbon dioxide is responsible for about half of the contribution greenhouse gases make to global warming. Since the beginning of the industrial revolution, the level of carbon dioxide has increased about 25 percent and is approaching the maximum amount that scientists believe has occurred naturally over the past million years. According to DOE, difficulties in estimating future levels may be due, in part, to problems in modeling fossil fuel emissions on a 100-year time scale and uncertainties in modeling natural ocean and terrestrial processes that emit carbon dioxide and remove it from the atmosphere.

To better estimate the growth of greenhouse gases, scientists have identified the need for (1) further research on the chemical, biological, and geophysical processes that affect changes in atmospheric concentrations and (2) improved, long-term monitoring of atmospheric trends. Federal agency scientists expect that the research they have planned and are undertaking will produce more precise estimates of increases in greenhouse gases. These estimates, in turn, should help researchers and policymakers to understand how and when these gases may affect the climate and to devise strategies to limit their growth.

Estimates of the Effects of Greenhouse Gases on Future Climate

According to current estimates of climate change made by five general circulation models, the average global temperature will increase by 3 to 9 degrees Fahrenheit over the next century, assuming a doubling of the effect of greenhouse gases. Even the lower of these estimates could be the most rapid temperature increase the earth has ever experienced. Although such temperature increases have not yet been detected, some scientists believe that the warming could soon become noticeable to the average person.

Some models also predict (1) greater warming near the poles than around the equator, (2) changing rainfall patterns, and (3) rising sea levels. However, the models are inconsistent on regional climate changes and specific time frames for changes. For example, a NOAA model estimated that summers would be drier than normal in the southeastern United States, while a NASA model estimated the opposite.

Limitations in the models affect their accuracy and are responsible for their differing results. First, general circulation models divide the earth into a gridwork of boxes, each usually 300 miles square. The large area covered by a box means that small-scale meteorological phenomena, such as thunderstorms and clouds, cannot be included in the models or must be simplified, and that variations in temperature and rainfall, for example, cannot be taken into account. Second, processes that may amplify warming or cooling effects are inadequately incorporated into the models. For example, the manner in which the models simplify complex interactions between the ocean and atmosphere accounts for some differences in their estimates.

Ongoing and planned research is addressing these limitations and is expected to improve estimates of climate change. Plans include (1) research to better understand climate processes, (2) long-term measurements of climate change, and (3) more computer resources. Improved estimates will help policymakers to develop a strategy to mitigate or prepare for possible climate changes.

Policy Issues

Although the extent, magnitude, and timing of global warming are uncertain, past and current emissions of greenhouse gases probably make warming unavoidable. National and international policymakers are discussing ways to reduce man-made emissions and to adapt to possible impacts of global climate change and risks that may result from delaying action. By acting now to reduce greenhouse gas emissions rather than waiting for better information, policymakers may minimize potentially harmful changes to the environment.

Developing a worldwide strategy to slow global warming will be economically and politically contentious because it will involve a decreased reliance on fossil fuels, which currently provide over 75 percent of the world's energy. Fossil fuel consumption can be reduced by improving the efficiency of energy use or by replacing fossil fuels with alternative energy sources, such as solar or nuclear power.

In preparing for global warming, policymakers must therefore weigh the risk of more adverse impacts by delaying action while they wait for additional scientific information against prematurely taking costly actions that may prove unwarranted. Nevertheless, it has been argued that actions can be taken now to reduce greenhouse gas emissions that will have other benefits, such as lessening dependence on foreign oil and improving air quality.

Recommendations

This report was intended to describe global warming research and policy issues and thus contains no recommendations.

Agency Comments

NASA and EPA generally agreed that the report was useful to policymakers, but NASA, DOE, and NOAA recommended including more current information. This report was therefore updated to reflect the final report of the Intergovernmental Panel on Climate Change, to be issued later this year. EPA also recommended adding information on the effects of climate on living systems, but GAO's intent in this report was to focus initially on estimates and causes of global climate change. NOAA and DOE advised including information on costs and benefits of emissions reduction. Recognizing that economic tradeoffs have to be considered in any emission reduction strategy, GAO nevertheless believes that actions could be implemented now that have benefits beyond reducing emissions.

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Abbreviations

CFC	chlorofluorocarbon
DOE	Department of Energy
DOI	Department of the Interior
EPA	Environmental Protection Agency
ERBE	Earth Radiation Budget Experiment
FEMA	Federal Emergency Management Agency
GAO	General Accounting Office
GCM	general circulation model
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute for Space Studies
GNP	gross national product
IPCC	Intergovernmental Panel on Climate Change
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OSU	Oregon State University
PPMV	parts per million by volume
TRMM	Tropical Rainfall Measuring Mission
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Introduction

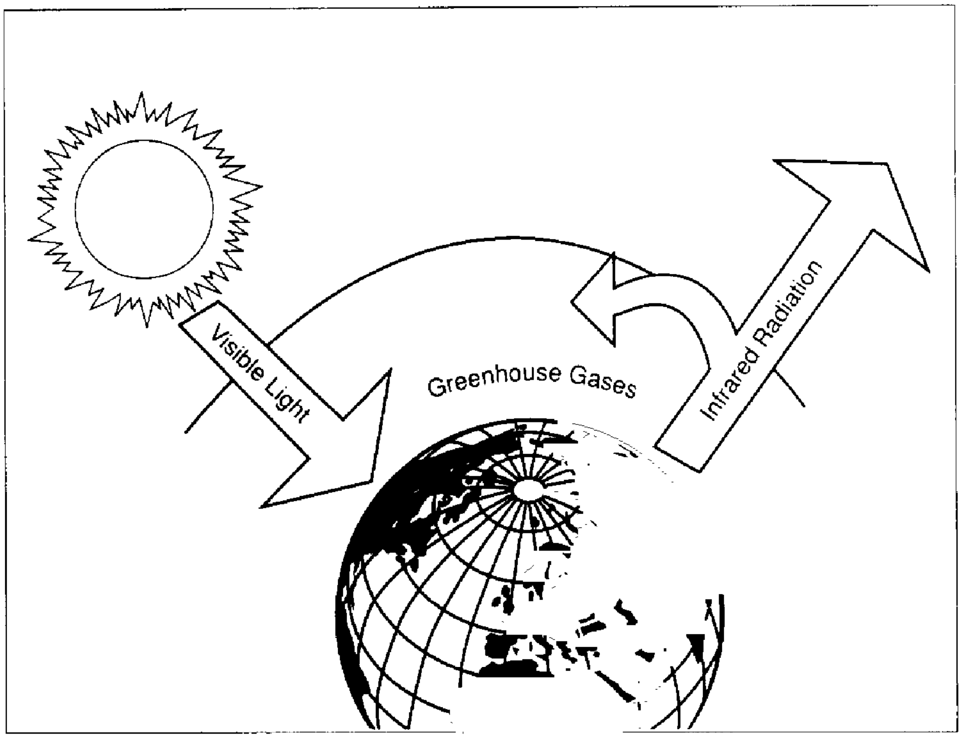
Growth in industry, agriculture, and transportation for over a century has resulted in the buildup of heat-trapping "greenhouse gases" that may be creating an unprecedented, worldwide environmental problem. As the earth warms rapidly under the effect of these greenhouse gases, species may become extinct, sea levels may rise, and weather and agricultural patterns may be altered. Given such potential changes, scientists and policymakers around the world are examining what can be done to prevent or mitigate an enhancement of the greenhouse effect.

Background

Climate and weather are determined by complex interactions of the atmosphere, land surface, snow, sea ice, and oceans, involving the exchange of energy within and among these components. These interactions vary considerably from day to day, month to month, and year to year. Changes in the amount of energy emitted by the sun, changes in the atmospheric composition (because of volcanic eruptions and emissions of aerosols and greenhouse gases), and changes in the earth's surface (such as deforestation) can also cause the earth's energy balance, and, hence, climate to vary.

Greenhouse gases—such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone—occur naturally in the atmosphere. They serve as a figurative thermal blanket that absorbs the earth's infrared radiation and re-radiates it downward, trapping part of the heat that would otherwise radiate into space. (See fig. 1.1.) This process warms the earth's surface and lower atmosphere so that an average global temperature of about 60 degrees Fahrenheit is maintained. Many scientists and policymakers are concerned, however, that if concentrations of these natural greenhouse gases and synthetically produced chloroflourocarbons (CFC) increase, the atmospheric temperature will also increase.

Figure 1.1: How the Greenhouse Effect Works



Source: Based on W.R. Moomaw, "The Basis of the Greenhouse Effect" (Washington, D.C.: World Resources Institute, Sept. 16, 1988), p. 2, and J.B. Smith and D.A. Tirpak (eds.), The Potential Effects of Global Climate Change on the United States, Environmental Protection Agency, draft (Washington, D.C. Oct. 1988), p. 2-3.

Computer Modeling of Climate Change

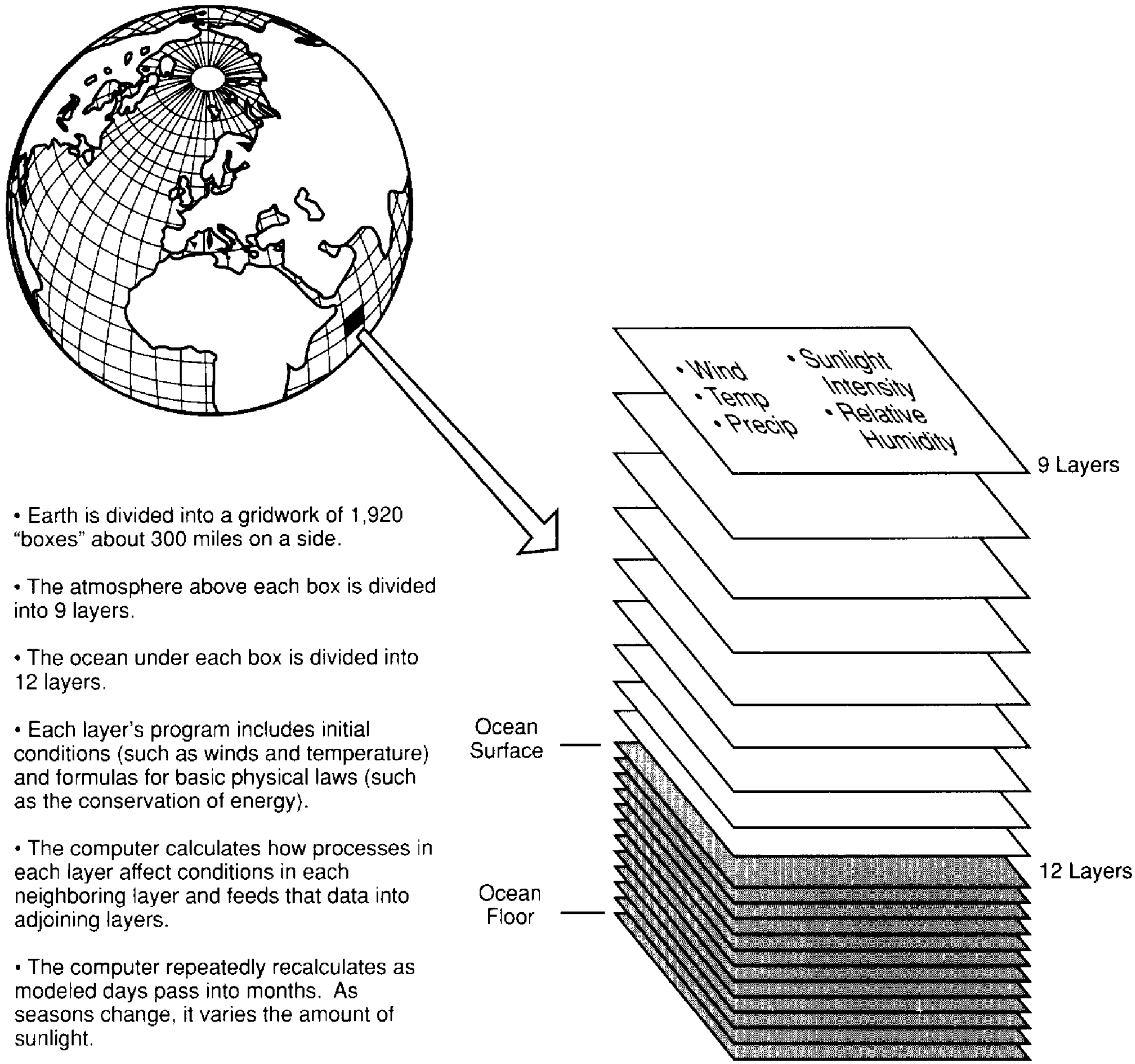
Scientists use complex computer models, called general circulation models (GCM), as one means of estimating climate changes based on variations in greenhouse gases.[1] GCMs apply equations representing basic physical laws, such as the conservation of energy, to the atmosphere, oceans, and ice sheets. These basic laws are then combined with more detailed processes, such as the reflectivity of clouds.

These equations are too complex to be solved exactly; consequently, modelers create a discrete number of grid boxes around the globe in which solutions to the equations are approximated, as shown in figure 1.2. Roughly, the grid boxes in some GCMs are about 300 miles by 300 miles. The size of the grid box determines the level of analysis (resolution). Anything that occurs on a smaller scale is not explicitly treated in

[1]EPA has noted that several other modeling and analytical techniques are used to study climate changes, such as radiative-convective models and chemical models. Like GCMs, each analytical tool has its strengths, weaknesses, and domain of usefulness.

the model, but is instead approximated within each grid box. These grid boxes allow scientists to compromise between the need to include relevant processes and interactions and the need to run the models on available computers in reasonable periods of time. Even so, 1 year of modeled time on a GCM might take 25 hours of supercomputer time; thus, each complete run would normally take thousands of computer hours.

Figure 1.2: How One General Circulation Model Works



- Earth is divided into a gridwork of 1,920 "boxes" about 300 miles on a side.
- The atmosphere above each box is divided into 9 layers.
- The ocean under each box is divided into 12 layers.
- Each layer's program includes initial conditions (such as winds and temperature) and formulas for basic physical laws (such as the conservation of energy).
- The computer calculates how processes in each layer affect conditions in each neighboring layer and feeds that data into adjoining layers.
- The computer repeatedly recalculates as modeled days pass into months. As seasons change, it varies the amount of sunlight.

Source Based on W Booth, "Computers and 'Greenhouse Effect' The Genesis of Understanding," The Washington Post, June 12, 1989, p A3.

Because different modelers use different methods to approximate processes that affect clouds, oceans, and seasonal cycles, each GCM differs somewhat in its computational structure. For example, some GCMs have day/night cycles, while others do not. In addition, most GCMs use very simple representations of the ocean (for example, representations not including ocean currents), each in its own way.

Several groups of scientists have been developing GCMs over the past 2 decades. In 1975, researchers at the National Oceanic and Atmospheric Administration's (NOAA) Geophysical Fluid Dynamics Laboratory reported the first attempt to use a full GCM to study carbon dioxide-induced climate change. Today, several federal agencies are using GCMS to study the potential climate impacts of increasing greenhouse gases: the National Aeronautics and Space Administration's (NASA) Goddard Institute for Space Studies, NOAA's Geophysical Fluid Dynamics Laboratory, the National Science Foundation's (NSF) National Center for Atmospheric Research, and DOE-funded research at Oregon State University.[2]

Federal Involvement in Global Climate Change Research

Federal research on global climate change is conducted primarily by seven federal agencies. All of this research relates directly or indirectly to the global warming issue. Research by these agencies encompasses the chemical, biological, and physical processes that affect climate change; the influence of human activities on global climate and vice versa; and ways to adapt to or limit global climate change.[3] Specifically,

- the Department of Energy (DOE) focuses on energy technology development, atmospheric research, modeling analysis, impact analysis, and economic analysis for potential responses;
- the Environmental Protection Agency (EPA) evaluates options to slow the rate of global climate change, assesses the effectiveness of such options in protecting environmental resources, and assesses feedback effects involving greenhouse gases;

[2]The Oregon State University model is now run by the University of Illinois. Other groups in the United States running GCMs include the University of California at Los Angeles, Colorado State University, and NASA's Goddard Space Flight Center. However, these groups do not study long-term climate change with their models.

[3]Recently, GAO examined federal agencies' coordination and U.S. participation in international activities concerning global warming activities (Global Warming: Administration Approach Cautious Pending Validation of Threat, GAO/NSIAD-90-63, Jan. 8, 1990) and DOE's research activities on global warming (Greenhouse Effect: DOE's Programs and Activities Relevant to the Global Warming Phenomenon, GAO/RCED-90-74BR, Mar. 5, 1990).

- NASA is responsible for earth science research from space, including broad scientific studies of the planet as an integrated system;
- the Department of Commerce's NOAA emphasizes improving estimates of climate change and the regional implications of that change, including climate research and modeling, oceanic and atmospheric monitoring and analysis, and the collection and management of climate data;
- NSF's Global Geosciences Program supports university-based basic research in earth, atmospheric, and ocean sciences;
- the U.S. Department of Agriculture (USDA) researches the climate's impact on agriculture and ecological systems and the impact of those systems on the climate; and
- the Department of the Interior's (DOI) U.S. Geological Survey (USGS) researches past climate changes and processes related to climate change, such as the interaction of hydrologic and ecological systems with climate.[4]

The funding devoted primarily to research on climate change by these agencies in fiscal year 1990 was approximately $660 million, and the proposed budget for fiscal year 1991 would increase funding to over $1 billion. Table 1.1 shows each agency's share of the research budget for fiscal year 1990 and the proposed budget for fiscal year 1991.

Table 1.1: Federal Agencies' Budgets for Research on Global Climate Change

Dollars in Millions

Agency	Fiscal year 1990	Fiscal year 1991
DOI	$13.3	$43.7
DOE	50.0	66.0
EPA	15.4	24.0
NASA	488.6	661.0
NOAA	18.0	87.0
NSF	55.0	103.0
USDA	21.2	47.4
Total	**$661.5**	**$1032.1**

Note: The U.S. Global Change Research Program includes climate, ecological, biogeochemical, and solid earth processes; human activities that affect such processes; and the sun's influence on the earth. Enhanced global warming is an important element in this research program.

Sources Committee on Earth Science and EPA.

[4]Several other agencies are involved in this issue. The Department of State is the lead agency for coordinating and setting policy for U.S. participation in international programs, and the National Academy of Sciences' Committee on Global Change is the federal advisory body for establishing priorities for research on global climate change.

Federal research on global warming is coordinated by the Committee on Earth Sciences, an interagency group of the Federal Coordination Council for Science, Engineering, and Technology, under the direction of the President's Science Advisor.

Objectives, Scope, and Methodology

The Chairman, Environment, Energy, and Natural Resources Subcommittee, House Committee on Government Operations, requested that we examine the science and policy issues concerning climate change. Specifically, our objectives were to

- describe what is known and not known about greenhouse gases,
- describe the strengths and limitations of models used to estimate global warming, and
- identify possible policy responses.

In fulfilling the first two objectives, we interviewed officials and reviewed relevant studies and reports at NSF headquarters and the NSF-funded National Center for Atmospheric Research; DOE headquarters and the DOE-funded climate research program at Lawrence Livermore National Laboratory; NASA headquarters, Goddard Space Flight Center, and Goddard Institute of Space Studies; and NOAA headquarters and its National Climate Program Office, Geophysical Fluid Dynamic Laboratory, and Aeronomy Laboratory. In addition, we interviewed officials at the Committee on Earth Sciences, EPA, the National Academy of Sciences, USDA, and USGS. However, we did not inventory all federal research being conducted on global warming because of the large number of projects currently underway and the breadth of topics being studied. Furthermore, new findings based on this research are frequently being reported in the scientific literature. This report discusses research reported as of October 1989. It was updated to reflect more recent findings as appropriate.

In addition, we attended several major conferences on climate change and spoke with representatives of several nonfederal organizations involved in global warming studies for information on the causes, effects, and estimates of global warming: Columbia University's Lamont-Doherty Geological Observatory, the Environmental Defense Fund, the Joint Oceanographic Institutions, the National Academy of Sciences' Committee on Global Change, the Natural Resources Defense Council, the Pacific Institute, Resources for the Future, the University Corporation for Atmospheric Research, the University of Maryland's Laboratory for Coastal Research, the University of Virginia, and the World Resources Institute.

In addressing the first objective, we gathered information on the life spans, rates of growth, sources, and radiative effects of greenhouse gases. We obtained information on research that is needed to address areas of uncertainty.

To pursue the second objective, we gathered information on general circulation models, which are a basis for climate change estimates. We compared the findings of four climate models funded by federal agencies—NOAA's Geophysical Fluid Dynamics Laboratory, NASA's Goddard Institute of Space Studies, NSF's National Center for Atmospheric Research, and Oregon State University (funded by NSF and DOE)—and obtained opinions from the researchers at these institutions and others in the scientific community on the models' strengths and limitations.[5] We chose these four modeling groups because they were identified as the only federally funded groups using general circulation models to study long-term climate change. Where appropriate, we also included findings from the climate model run by the United Kingdom's Meteorological Office. In meetings with the modeling groups, we also discussed uncertainties surrounding the causes and effects of global warming. In addition, we visited Lawrence Livermore National Laboratory, which conducts research on climate modeling, including a project comparing climate models. At Lawrence Livermore Laboratory, we obtained information on how the various models used to estimate climate change compare in structure and output. We also reviewed the draft executive summary of a report by the Intergovernmental Panel on Climate Change (IPCC) containing a scientific assessment of climate change.

As part of our second objective, we assessed how research on the effects of climate change is influenced by limitations in the climate models. Using one of the most certain effects of global warming, a rise in sea level, as a case study, we gathered information on how well effects can be assessed, given the uncertainties in forecasting climate change. We interviewed scientists at EPA, Joint Oceanographic Institutions, and the University of Maryland's Coastal Research Laboratory who have been studying the rise in sea level associated with climate change. We gathered information on the effects of a rise in sea level, the populations

[5]We did not interview researchers at Oregon State University. During our review, the chief climate modelers left the university. Consequently, the university no longer conducts climate research.

that would be most greatly affected, and time frames for the expected rise.

To address our third objective, we obtained information on policy issues from the following environmental and industry groups: the American Nuclear Energy Council, the American Petroleum Institute, the Center for Energy and Environmental Studies at Princeton University, the Climate Institute, the Edison Electric Institute, the Electric Power Research Institute, the Environmental and Energy Study Institute, the Motor Vehicle Manufacturers Association, the National Association of Manufacturers, the National Coal Association, the Natural Resources Defense Council, Public Citizen, Renew America, Resources for the Future, the Solar Energy Industries Association, the U.S. Public Interest Research Group, and Worldwatch Institute. We also discussed responses to global warming with officials at federal agencies, particularly EPA and DOE.

Our work was conducted between November 1988 and October 1989 in accordance with generally accepted government auditing standards. Information was updated through August 1990. DOE, EPA, NASA, NOAA, and NSF were given the opportunity to comment on a draft of this report. NSF declined to respond. The other agencies' responses are in appendixes I through IV.

Greenhouse Gases Increasing at Uncertain Rate

Fossil fuel combustion and other human activities are emitting gases into the atmosphere that could result in long-term changes to global climate. The increased atmospheric warming that may be caused by these gases is known as an enhanced greenhouse effect, which, until recently, was believed to be caused solely by increases in carbon dioxide. It is now known that other gases— such as methane, CFCs, nitrous oxide, and ozone—in the lower atmosphere, when taken together, are also very important and may soon surpass carbon dioxide as the primary contributors to enhanced global warming. The atmospheric concentrations of these gases are increasing, although their future rates of growth are uncertain because the biological, physical, and chemical processes that regulate their atmospheric concentrations are not fully understood. The sources of CFCs and carbon dioxide have been identified better than the sources of the other greenhouse gases. The research being undertaken and planned by several federal agencies is expected to help resolve the uncertainties surrounding the sources and processes that regulate the concentration of greenhouse gases.

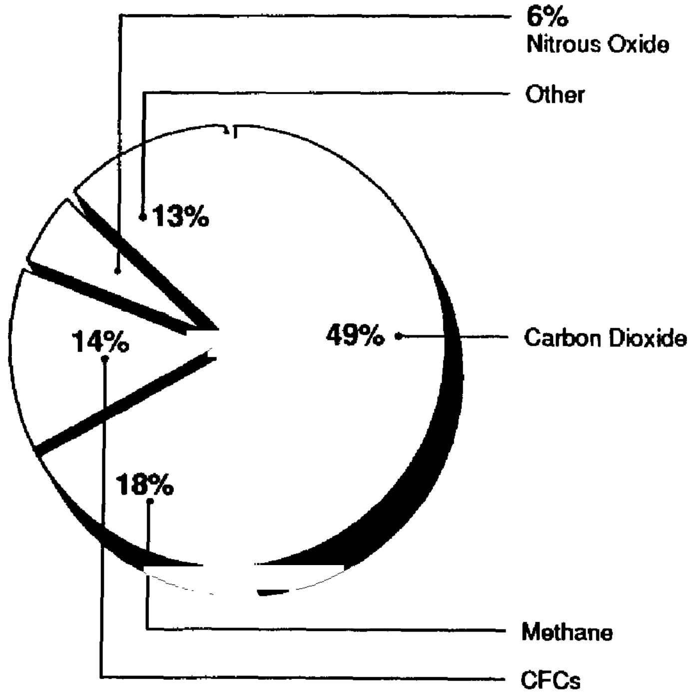
Agreement Exists on the Greenhouse Effect of Certain Gases

For nearly 100 years, scientists have known that a buildup of carbon dioxide in the atmosphere has the potential to warm the earth by enhancing the natural greenhouse effect that maintains the average global temperature at about 60 degrees Fahrenheit. Over the past 10 years, however, awareness has grown in the scientific community that other greenhouse gases, when taken together, have a warming effect comparable to that of carbon dioxide. Almost all climate scientists believe that increases in greenhouse gases are very likely to raise the average global temperature. This belief is based on calculations derived from well-established physical principles and is supported, in part, by the study of other planets and by analyses of past glacial and interglacial climates on earth that show a close relationship between changes in global temperature and changes in the atmospheric concentration of some greenhouse gases.

Carbon Dioxide Is Responsible for Half the Enhanced Greenhouse Warming

Scientists estimate that during the 1980s about half of the greenhouse gases' contribution to global warming was due to increases in carbon dioxide and half was due to increases in the other greenhouse gases combined (see fig. 2.1). The relative contribution of each gas to increased atmospheric heating is determined by its ability to absorb infrared radiation and its atmospheric abundance. Atmospheric abundance is determined by the quantities being emitted and the lifespan of the gases in the atmosphere. For example, methane is about 25 times more efficient per molecule in absorbing infrared radiation than carbon dioxide, but its contribution to atmospheric warming is currently much lower than carbon dioxide because methane is not as abundant.

Figure 2.1: Contributions of Greenhouse Gases to Global Warming During the 1980s



Note: The "Other" category includes halons, tropospheric ozone, and stratospheric water vapor. The percentages are based on estimates of increases in concentration of each gas during the 1980s.
Source. D.A. Lashof and D.A. Tirpak (eds.), Policy Options for Stabilizing Global Climate, EPA, draft (Washington, D.C.: Feb. 1989), p. II-61.

Table 2.1 summarizes information on the atmospheric concentration, lifetime, and atmospheric heating contribution of several greenhouse gases. It is based on a 1988 DOE report that evaluated the current scientific understanding of basic information on numerous greenhouse gases and a similar report by EPA.[1]

[1]This information has been updated to reflect more recent findings by the Intergovernmental Panel on Climate Change.

Table 2.1: Summary of Information on Several Greenhouse Gases

Greenhouse gas	Atmospheric concentration (ppmv)[a]	Atmospheric lifetime (years)	Atmospheric heating contribution per molecule relative to carbon dioxide
Carbon dioxide	353	50 to 200	1
Methane	1.72	7 to 10	About 25
Nitrous oxide	0.31	About 150	About 230
CFC-11	0.00028	65	About 16,000
CFC-12	0.000484	130	About 21,000

[a]Parts per million by volume.

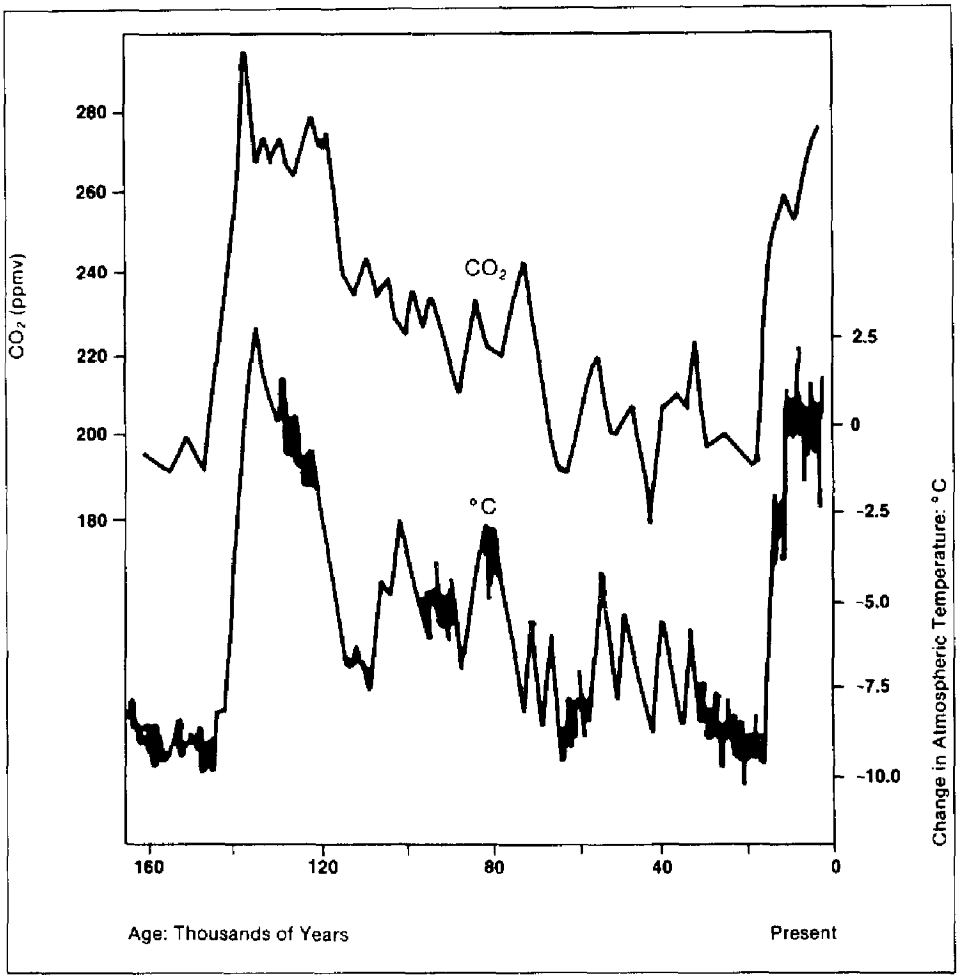
Sources: D.J. Wuebbles and J. Edmonds, A Primer on Greenhouse Gases, U.S. Department of Energy, Office of Energy Research (Washington, D.C.: March 1988), pp. 2-39, and Lashof and Tirpak, Policy Options for Stabilizing Global Climate, pp. II-29 to II-39. This information has been updated in "Policymakers Summary of the Scientific Assessment of Climate Change," IPCC, draft (May 25, 1990), p. 7.

Historic Increases in Carbon Dioxide Have Been Associated With Climate Change

Most scientists believe that the eventual response to increases in greenhouse gases will very likely be, on average, global warming. There is historic evidence, based on analyses of air samples trapped in ice, that long-term changes in temperature are correlated with changes in the atmospheric concentration of carbon dioxide. Analyses indicate that the carbon dioxide level varied between a low near 200 parts per million in cold, glacial times and a high near 280 parts per million (but currently about 350 parts per million) in warm, interglacial times. Recent analyses show direct evidence of these trends over the last 160,000 years.[2] As shown in figure 2.2, two large increases in temperature and carbon dioxide occurred about 15,000 years ago and nearly 140,000 years ago. The low carbon dioxide concentrations generally correspond to the glacial conditions that prevailed for most of the last 100,000 years. Whether the level of carbon dioxide was a response to or contributed to the temperature changes is uncertain.

[2]J. M. Barnola et al., "Vostok Ice Core Provides 160,000-year Record of Atmospheric CO^2," Nature, vol. 329 (1987), pp. 408-14.

Figure 2.2: Carbon Dioxide Levels and Temperature Changes Over the Last 160,000 Years



Source: Barnola et al., "Vosak Ice Core Provides 160,000-Year Record," p. 410.

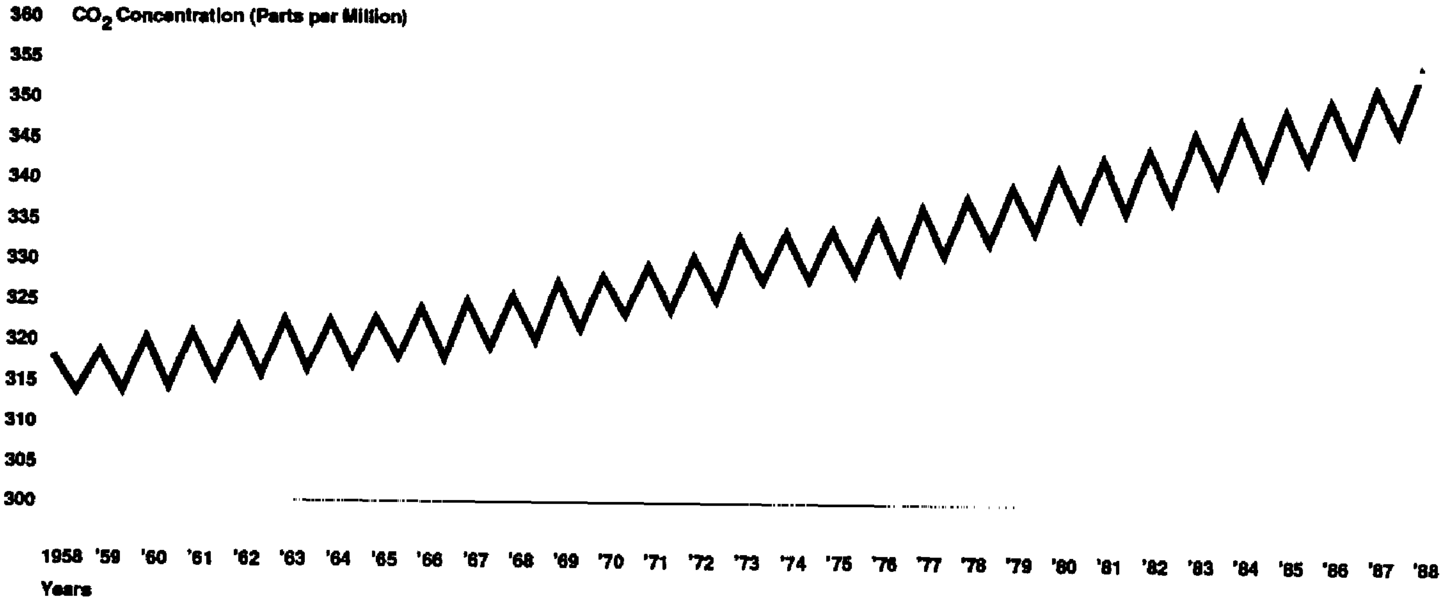
Future Growth of Greenhouse Gases Uncertain

The atmospheric concentration of carbon dioxide has been increasing at least since the beginning of the industrial revolution. The concentrations of other greenhouse gases are also increasing. Estimates of future atmospheric levels of carbon dioxide and some of the other greenhouse gases, however, are uncertain primarily because the future emission rates are uncertain.

Carbon Dioxide Levels Increasing

Carbon dioxide—produced by fossil fuel combustion, deforestation, cement manufacture, and respiration by living organisms—has increased in the atmosphere by about 25 percent since the beginning of the industrial revolution. Measurements taken by NOAA since 1958 reveal a continuous and possibly accelerating increase in the mean annual concentration, as shown in figure 2.3. In 1958, the concentration was about 315 parts per million; and in 1988, it was over 350 parts per million. According to a DOE study, all of the increase is due to human activities, predominantly fossil fuel combustion.[3]

Figure 2.3: Concentration of Atmospheric Carbon Dioxide at Mauna Loa Observatory, Hawaii



Note: The annual cycle shown in the figure is a result of the seasonal photosynthetic activity in the Northern Hemisphere. That is, during the growing season more carbon dioxide is drawn out of the atmosphere by photosynthesizing plants than is released into it by respiration; in winter, the opposite is true.
Source: NOAA.

Records at other NOAA sites, such as Antarctica, confirm that this increase is a global phenomenon. These records indicate that the carbon dioxide concentration in the atmosphere has increased by nearly 10 percent during the last quarter century and is approaching the apparent

[3]D. J. Wuebbles and J. Edmonds, A Primer, p. 8. According to comments received from NOAA, this statement is somewhat strong in light of the present understanding of natural sources and "sinks" in the global carbon cycle. A major debate is currently underway on whether a major Northern Hemisphere "sink" exists.

limits of natural variation characteristic of the glacial-interglacial cycles of the past million years.[4]

Other Greenhouse Gases Also Increasing

According to published reports, other greenhouse gases are similarly increasing in concentration. (See table 2.2.) Although these gases occur naturally (except CFCs), their increases are caused nearly exclusively by human activities.

Table 2.2: Annual Growth Rates and Sources of Greenhouse Gases

Gas	Annual growth rate (percent)	Sources
Carbon dioxide	About 0 5	Fossil fuel combustion Deforestation Cement manufacturing
Methane	0.9	Wetlands Rice paddies Cattle and sheep Termites Biomass burning[a] Natural gas and mining losses Solid waste
Nitrous oxide	0.25	Fossil fuel combustion Fertilized and cultivated soils Biomass burning[a]
CFCs	4	Refrigerator coolants, air conditioner coolants, insulating and packing foam, and aerosol propellants
Ozone	Uncertain	Chemical interactions of hydro-carbons, carbon monoxide, methane, and nitrogen oxide

[a]Biomass is dry organic matter.

Sources: Smith and Tirpak, Potential Effects of Global Climate Change on the United States, pp 2-4, 2-10, and 2-11; and Wuebbles and Edmonds, Primer on Greenhouse Gases, pp. 10-40. This information has been updated in "Policymakers Summary," IPCC, p. 7.

For example, the methane concentration increased in the atmosphere by about 1 percent per year from the early 1950s through the early 1980s.[5] Analyses of air trapped in ice indicate that the atmospheric concentration of methane started increasing over the last several hundred years, after being constant for 10,000 years or more. It has increased to

[4]R.H. Gammon, et al., "History of Carbon Dioxide in the Atmosphere," in J.R. Trabalka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle, DOE (Washington, D.C.: Dec. 1985), p. 27. The authors discuss the evolution of the concentration of carbon dioxide in the earth's atmosphere during the last 100 million years.

[5]Wuebbles and Edmonds, Primer on Greenhouse Gases, p. 22.

approximately double the natural levels of several centuries ago. Since this increase corresponds with the growth of the human population and industrial society, it is believed to be a result of increased methane emissions from the expansion of rice agriculture, the raising of ruminant animals such as cattle and sheep, the storage of organic waste in landfills, and the mining and use of fossil fuels.

Estimates of Future Atmospheric Levels Uncertain

It is uncertain whether the current growth rate in the atmospheric concentrations of carbon dioxide and other greenhouse gases will continue, according to scientists.[6] In some cases, uncertainty is due to insufficient understanding of the natural processes that affect their atmospheric levels and/or difficulties in predicting human activities a century from now.

Although the sources of carbon dioxide and CFCs have been identified better than the sources of other greenhouse gases, uncertainties still remain in predicting future atmospheric concentrations. For example, according to a DOE study, the principal uncertainty hampering accurate estimates of atmospheric carbon dioxide levels a century from now is the future rate of emissions from fossil fuel combustion.[7] Some of the largest uncertainties surrounding future emissions concern future economic and population growth rates. Uncertainties in projected energy use and choices of energy technologies are factors that make such forecasts difficult.

Additionally, DOE reported that estimates are hampered by unknowns about the role the biosphere and oceans play in regulating carbon dioxide concentration in the atmosphere. Calculations of worldwide fossil fuel usage indicate that over twice as much carbon dioxide is injected into the atmosphere yearly than can be accounted for by the increases in atmospheric concentration that are being measured at observation stations. The remaining carbon dioxide, scientists believe, is being removed by the photosynthesis of green plants and by the chemical and biological interaction of the ocean with the atmosphere. There are uncertainties, however, in apportioning the amounts of carbon

[6]EPA concurs that estimates of the future growth of greenhouse gas emissions are uncertain. However, EPA notes that projections of future emissions are being made and used by the United States and other countries for planning purposes. EPA further states that these projections are reasonable scenarios for the future, and using these scenarios, the United States and other countries can begin to plan and determine the types of reductions that will be necessary to limit greenhouse gas emissions.

[7]M.P. Farrell (ed.), Master Index for the Carbon Dioxide Research State-of-the-Art Report Series, DOE, Office of Energy Research (Washington, D.C.: Mar. 1987), p. 6.

dioxide being removed from the atmosphere between plants and the oceans, although most atmospheric scientists believe that removal by the ocean is substantially larger.

Future growth in the atmospheric concentration of methane is also uncertain, according to a report by DOE, because of insufficient data on the amount of methane emitted by natural and man-made sources.[8] As a result, the ranges estimated for individual sources are large. For example, according to the DOE report, wetlands are emitting between 60 billion and 160 billion metric tons of methane per year, and rice paddies are emitting between 40 billion and 100 billion metric tons per year. Additionally, growth rates are uncertain because enhanced global warming could possibly increase the release into the atmosphere of large quantities of methane frozen in the ice and soil in arctic and subarctic regions.

Uncertainties also surround scientists' understanding of the future growth rates of other greenhouse gases. For example:

- Although the sources of nitrous oxide have been reasonably identified, the processes and conditions under which more or less nitrous oxide is released from the soil need to be better understood.[9]
- Measurement techniques for determining reliable, long-term global ozone trends need to be developed.[10]

Despite uncertainties in the sources and rates of future growth, the Director of NOAA's Aeronomy Laboratory predicts that within the next decade the greenhouse gases other than carbon dioxide, when taken together, will surpass carbon dioxide as the primary contributors to potential global warming.[11]

[8]Wuebbles and Edmonds, Primer on Greenhouse Gases, pp. 20-25.

[9]P.M. Vitousek, "Perspectives on the Nitrogen Cycle," in 1988 Global Change Institute on Trace Gases and the Biosphere, Office for Interdisciplinary Earth Studies, University Corporation for Atmospheric Research, draft (Boulder, Co.: Jan. 1989), p. 9.

[10]Wuebbles and Edmonds, Primer on Greenhouse Gases, p. 18.

[11]In its recent scientific assessment, IPCC asserted with confidence that carbon dioxide has been responsible for over half the enhanced greenhouse effect in the past and is likely to contribute as much in the future. See "Policymakers Summary," IPCC, p. 1.

Need for Improved Understanding of Processes Controlling Greenhouse Gases and for Better Data

Scientists have identified two areas where further work is needed to improve their understanding of greenhouse gases:

- Better experimental and theoretical understanding of the biological, chemical, and geophysical processes that control the emission and uptake of greenhouse gases.
- Better observational data bases.

The need for a better understanding of the processes that control the emission and removal of greenhouse gases was repeatedly mentioned by scientists we interviewed and in published reports. For example, the National Academy of Sciences identified the need to improve the understanding of primary ecosystem processes that determine the movement of greenhouse gases between the land and atmosphere. DOE cited the need to better understand the processes that release into and remove from the atmosphere carbon dioxide and other greenhouse gases.

Improved observational data on the atmospheric concentration of greenhouse gases, particularly long-term monitoring, will provide data to improve scientists' understanding of these processes. According to scientists we spoke with, the observational data could be improved by the addition of monitoring stations and more vertical measurements of the gases' atmospheric concentrations. Current measurements are taken predominantly at ground level, and measurements of the distribution of greenhouse gases with altitude would improve scientists' knowledge of the sources of these gases and the processes that remove them from the atmosphere. Additionally, the monitoring techniques for ozone in the lower atmosphere need to be improved to determine ozone's annual growth rate (see table 2.2).

The research underway or planned at several federal agencies addresses these needs and is expected to improve scientists' understanding of greenhouse gases. The U.S. Global Change Research Program recognizes the need for more process studies and improved observational data and has proposed new research or augmentations to existing research to address these needs.[12] For example, the Global Ocean Flux Study—undertaken jointly by DOE, NASA, NOAA, and NSF—was expanded in fiscal

[12]The U.S. Global Change Research Program was developed by the Committee on Earth Sciences as part of the President's fiscal year 1990 budget for research on global climate change. This program sets forth a comprehensive plan for such research to be undertaken by DOE, EPA, NASA, NOAA, NSF, USDA, and USGS. The program assesses current agency programs, identifies the highest priority areas of needed research, and outlines research initiatives for fiscal year 1990 and/or augmentations by federal agency. The Committee on Earth Sciences expects to update this plan yearly.

year 1990 to focus on processes controlling the global marine carbon cycle, emphasizing the biological processes that control the movement of carbon into and out of the ocean. This work is proposed to be funded at $5.8 million in fiscal year 1990.

In addition, NOAA's Radiatively Important Trace Species Program undertakes laboratory and field studies to better understand the greenhouse gases other than carbon dioxide and maintains long-term measurements of these gases. There are plans to expand the program in fiscal year 1990 to set up monitoring stations to measure ozone concentrations in the lower atmosphere and to measure over time the distribution of ozone and other greenhouse gases at different altitudes.

GAO's Observations

Atmospheric concentrations of greenhouse gases such as carbon dioxide, methane, CFCs, and nitrous oxide are increasing, and some are approaching or have already exceeded historic levels. However, estimates of future atmospheric levels cannot be strongly relied upon because the sources of some of these gases and the processes that affect their atmospheric concentration are not adequately understood. Problems with the estimates add another degree of uncertainty to projections of future climate change.[13] These estimates are discussed in chapter 3.

The research being planned and undertaken by federal agencies is intended to reduce these uncertainties and improve estimates of future atmospheric levels of greenhouse gases. Improved estimates are important to understand how and when greenhouse gases may affect the climate and to determine strategies to limit their growth. Such strategies are discussed in chapter 4.

Agencies' Comments

EPA commented, in general, that this report represents a substantial compilation of ongoing work and achieves a well-balanced view of the issues. However, EPA said that some issues presented in this chapter required further elaboration. Where appropriate in the chapter, we have included additional points provided by EPA on

[13]EPA emphasized, however, that there is a strong scientific consensus that there will be an increase in concentrations of greenhouse gases resulting in increased temperatures.

- the use of emission scenarios by the United States and other countries for planning purposes despite the uncertainties in estimates of future growth of greenhouse gas emissions and
- the strong scientific consensus that there will be an increase in the concentration of greenhouse gases resulting in increased temperature.

NASA applauded our efforts to address the complex and important issues concerning global warming, but believed that the depth and timeliness of the report were handicapped in two ways. First, the executive summary oversimplified the diverse and complex issues that were presented in the body of the report. NASA urged a careful reading of the main body of the report to understand issues such as the distinction between deforestation and fossil fuel burning as sources of carbon dioxide at different times in history and the uncertainties regarding the loss mechanisms for carbon dioxide, which are discussed in chapter 2.

Second, NASA believed that the report was limited by having to treat a rapidly evolving body of scientific knowledge while being constrained to rely on published material. In particular, NASA referred to a draft report by IPCC that will be released later this year. According to NASA, this report will present important new findings on estimates of the atmospheric lifetime of carbon dioxide, discussed in chapter 2, as well as several other issues discussed in chapter 3. DOE and EPA also commented that information from the IPCC report should be included in this report.

Although the IPCC report is not issued, we were able to obtain a draft of the executive summary. We have updated information in the text—such as the atmospheric lifetime of carbon dioxide—to reflect these recent estimates.

NASA also believed that this chapter neglected other factors that affect the earth's energy balance and hence climate. We agreed with this point and added that information to chapter 1.

Global Warming Estimates Expected to Improve as Research Continues

Scientists use mathematical models—general circulation models (GCM)—to estimate the effect of greenhouse gases on the future global climate. These models agree that the average global temperature will increase over the next 100 years. There is little consensus, however, on the specific magnitude, timing, and regional distribution of this climate change.

This lack of consensus on the specifics of climate change is due to the limitations of the models themselves. GCMs are rough approximations of the atmosphere-ocean system and do not fully treat many important climate processes. The limitations affect not only the consensus among models but also diminish the usefulness of their results for research on the effects of climate change. The models' limitations are expected to decrease over the next 5 to 10 years if improvements are made in data, computing power, and scientists' understanding of the processes involved.

Estimates by Climate Models

Five major GCMs estimate that with the radiative equivalent of a doubling of carbon dioxide, the average global temperature will increase over the next century.[1] The amount of warming estimated varies from 1.6 to 5.2 degrees Celsius. The models also estimate greater warming near the poles, changing rainfall patterns, and rising sea levels. However, there is little consensus on many aspects of temporal or regional changes.

Evaluations of Models

To evaluate how well the models estimate climate change, modelers have tested their ability to reproduce some features of today's climate and past climates. According to most scientists, the models are generally accurate in reproducing today's climate and seasonal cycle on a global scale. Modelers have also assessed the ability of GCMs to reproduce past climates and have found that the models do well at simulating a few features of ancient paleoclimates. The successful simulation of past climate cycles, coupled with successful simulations of general features of the relatively warm present climate, indicates to researchers that the models are capable of estimating a wide range of climatic conditions.

[1]The radiative equivalent of a doubling of carbon dioxide means that the radiative effects of other greenhouse gases are included in the models by assuming that their increases are part of the carbon dioxide doubling. Modelers usually instantaneously double carbon dioxide as a convenient future scenario. Most models estimate that such a doubling could occur sometime during the twenty-first century. These estimates, however, are uncertain, as discussed in ch. 2. Recently, some models—including those at NASA, the Geophysical Fluid Dynamics Laboratory, and the National Center for Atmospheric Research—have used more realistic incremental increases in greenhouse gases to study the effect of their gradual accumulation on climate.

This capability provides more confidence in the results of these models when they are used to study carbon dioxide-induced climate change.

In many assessments, however, the models do not perform well, such as in testing the representations of individual physical components of the models. For example, a model may estimate average cloudiness well, but represent the amount of warming produced by clouds poorly. In addition, the models' ability to represent regional climate shows results that vary not only in magnitude but even in the direction of change for many regions. These assessments expose several of the models' limitations: They are inconsistent in estimating regional effects and representing small-scale processes, such as clouds. These and other limitations in GCMs are discussed later in this chapter.

Unprecedented Temperature Increases

For the radiative equivalent of a doubling of atmospheric carbon dioxide (which could occur as early as 2030), the models estimate a 1.6- to 5.2-degree Celsius (3- to 9-degree Fahrenheit) warming, as shown in table 3.1. For comparison, the warmest time during the past 100,000 years was only about 1 degree Celsius warmer than today. That is, if a doubling of carbon dioxide raises the temperature by even the low estimate of 1.6 degrees Celsius, the results will be beyond the range of any changes in average temperature that have existed during recent history, and the rate of temperature increase could be the most rapid the earth has ever experienced.

Table 3.1: Average Global Warming Estimated by GCMs for a Doubling of Carbon Dioxide

Research institution	Estimated warming by GCM (degrees Celsius)
United Kingdom Meteorological Office	5.2
Goddard Institute for Space Studies	4.2
Geophysical Fluid Dynamics Laboratory	4.0
Oregon State University	2.8
National Center for Atmospheric Research	1.6

Although these models point to substantial warming by the middle of the next century, the interim increases in temperature are uncertain. Researchers at Goddard Institute for Space Studies (GISS) have shown that their model indicated a tendency toward warming in the 1980s, but that in most regions the warming shown by the model was less than the natural variability. This variability—weather fluctuations from year to year—provides some cool years despite the slight overall warming trend and makes the detection of global warming difficult over the span of a few years. In the 1990s, according to the GISS model, the warming will be comparable to the variability of many regions, and by the 2010s, the entire globe will experience noticeable warming. Thus, although the effects of greenhouse warming have not been large enough to date to distinguish from natural variation, some scientists believe that the warming could soon become detectable by scientists and more noticeable to the average person.[2]

Other Features of Climate Change Estimated by Models

Modelers are less certain about the timing, magnitude, specific features, and effects of the warming than they are about the estimate that warming will occur. The Director of the Geophysical Fluid Dynamics Laboratory (GFDL) provided his estimates of the probability of certain climate changes, derived from the GFDL model and observational analyses. The results shown in table 3.2 suggest that changes such as increasing arctic warming and increasing global precipitation are very probable in a world where the amount of carbon dioxide has doubled. As the earth warms, sea ice and snow cover in the arctic region may melt, thereby reducing surface reflectivity and allowing still more absorption of solar radiation, which would further warm this region. Global average precipitation is also expected to increase as evaporation increases.[3]

[2]See J. Hansen, et al., "Prediction of Near-Term Climate Evolution: What Can We Tell Decision-Makers Now?" in Preparing for Climate Change, Proceedings of the First North American Conference on Preparing for Climate Change (Washington, D.C.: Government Institutes, Inc., Oct. 27-29, 1987), pp. 35-47. Other scientists caution that there is room for doubting such predictions.

[3]Researchers at GISS have found that greenhouse warming may increase the frequency of conditions of extreme moisture as well as extreme drought. They report that the impact of global warming on droughts and storms provides no evidence that there will be regional "winners" if greenhouse gases continue to increase rapidly. This finding has not been substantiated by other models and, therefore, is controversial.

Table 3.2: GFDL Estimates of Climate Change

Expected effect	Confidence[a]
Global average surface warming	Very probable
Global average precipitation increase	Very probable
Arctic winter surface warming	Very probable
Reduction of sea ice	Very probable
Northern high latitude precipitation increase	Probable
Summer continental dryness/warming	Probable
Rise in global mean sea level	Probable
Regional vegetation changes	Uncertain
Tropical storm increases	Uncertain
Details of next 25 years	Uncertain

[a]"Very probable," effect has more than a 90-percent chance of occurring; "probable," effect has more than about a 67-percent chance of occurring; "uncertain," effect has been hypothesized but evidence for its occurrence is inadequate.

Source: Testimony by Dr. Jerry Mahlman, Director, GFDL, before the House Committee on Appropriations, Subcommittee on Foreign Operations, Export Financing and Related Programs, Feb. 21, 1989

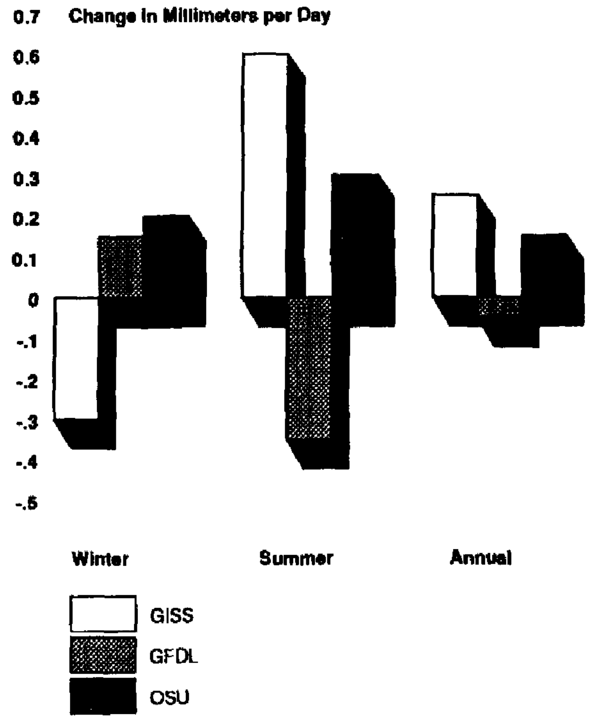
GCMs Lack Agreement on Regional Estimates

Although GCMs agree on some global average variables, the effects of increased amounts of greenhouse gases are less clear on a regional level. All models show an increase in global average temperature, but the regional temperature changes estimated often differ substantially in magnitude. For example, the GISS, GFDL, and Oregon State University (OSU) models all estimate an average warming over the United States. However, the annual average increase in temperature ranges from 3 degrees Celsius for OSU, to 4.3 degrees Celsius for GISS, to 5.1 degrees Celsius for GFDL.

The models also disagree on regional precipitation, as shown in figure 3.1. Although all three models estimate that the average annual precipitation in the United States will increase, their estimates of regional and seasonal distribution varied greatly. For example, one version of the GFDL model estimated that summers in the southeastern United States would be drier than normal, whereas a GISS model estimated that conditions would be wetter. This lack of agreement on regional impacts limits the models' usefulness for studying local climate changes.[4]

[4]Agreement on regional effects, however, would not ensure accuracy. Independent measures are needed to verify the models' estimates.

Figure 3.1: Precipitation Estimates for the Southeastern United States



Source: Smith and Tirpak, Potential Effects of Global Climate Change in the United States, p. 6-11.

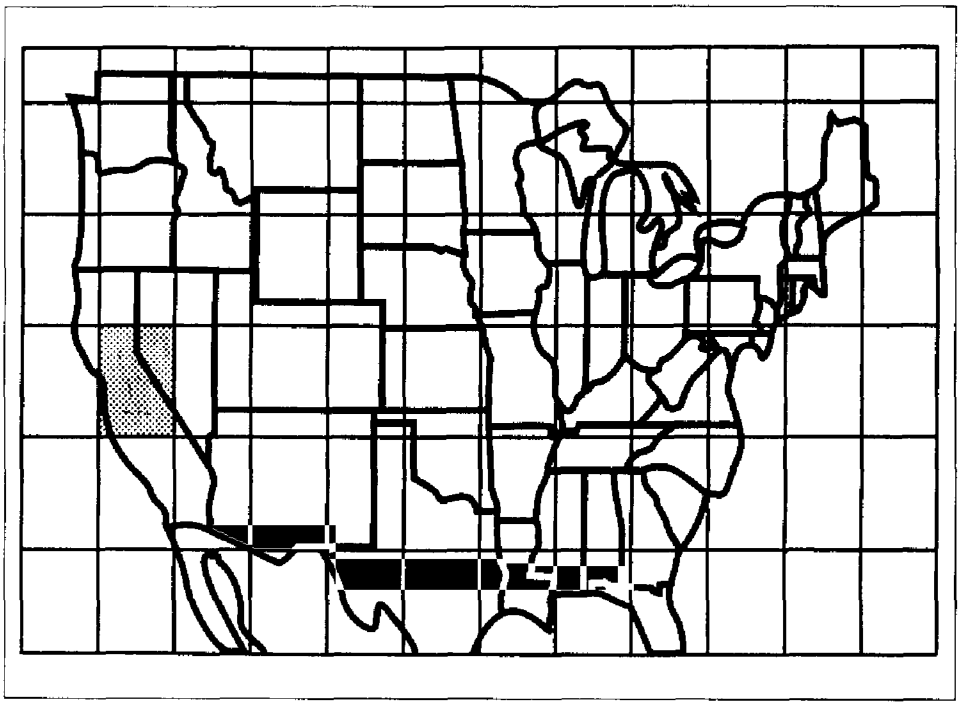
Models' Limitations

According to scientists we spoke with, several limitations in the models affect the accuracy of their estimates and are responsible for the lack of agreement among models. Because no model contains sufficient detail to simulate the atmosphere's full complexity, results are approximate and vary from model to model. GCMs do not perform calculations for every part of the earth's surface or atmosphere because the amount of data and computer capacity required would be prohibitive. Instead, calculations are solved at widely spaced grids, which preclude many important small-scale climate phenomena from being included. In addition, the models do not fully treat a number of feedback processes that could intensify or lessen global warming, such as changes in cloud cover. Similarly, ocean processes may alter climate change, but are omitted by many of the GCMs' simplified representations.

Grids Are Widely Spaced Within the GCMs

According to scientists we met with, a primary limitation of GCMs is their use of widely spaced grids. GCMs give outputs in grid boxes that vary in size from 4 degrees by 5 degrees to as much as 8 degrees by 10 degrees. Figure 3.2 shows 4-degree by 5-degree grid boxes from a GCM overlaid on a map of the United States. The grid boxes are about as large in scale as Colorado. Within each box, the actual climate may vary considerably. For example, the weather in western Nevada may be quite different from San Francisco, but both are in the same grid box, as seen in the shaded area. GCMs do not account for variations within each grid box, but instead estimate average climate conditions for the entire box. Thus, GCMs provide a single value for temperature, rainfall, and other variables for the entire grid box.

Figure 3.2: GCM Grids (Measuring 4 by 5 Degrees) **Over the United States**



Low resolution affects not only the precision of the output but also its usefulness. Since the output is a set of variables for an area about 300 miles by 300 miles, these data cannot be used to analyze smaller regions unless additional methods are applied. Low resolution also limits the ability of planners to use data from the GCMs in developing adaptation strategies. The primary obstacle to obtaining regional resolution is computing power. For example, 60-mile grid spacing would take 500 times the current computing power.

Models Describe Natural Processes in a Simplified Manner

According to the scientists we spoke with, a second fundamental problem in developing climate models has been the accurate representation of key processes, known as parameterization. Because important variables, such as clouds, do not occur on scales as large as a GCM grid, scientists approximate their effects. Climate models include a number of parameterizations, such as the role of clouds for water and energy transfer in the atmosphere. Scientists are still learning how to incorporate processes on small spatial and temporal scales into the large-scale models. As yet, they have not resolved how small-scale processes interact with large-scale processes; consequently, the influence of the regional features on the global system is uncertain.

Models Poorly Represent or Omit Important Processes

Introducing greenhouse gases into the atmosphere causes the earth's system to seek a new equilibrium climate in several ways. Often called climate feedbacks, these responses include changes in water vapor, ice cover, clouds, vegetation, and the oceans. The net effect of these feedbacks, some amplifying warming and some cooling, determines the new equilibrium climate reached after an increase in greenhouse gases. According to the scientists we spoke with, some feedbacks are incorporated well in the models, some are poorly represented, and others are omitted. For example, one researcher has pointed out that the models ignore some mitigating or cooling factors, such as sulfur dioxide emissions from coal-burning power plants. Sulfur dioxide could cause clouds to brighten and reflect incoming solar radiation away from the earth.[5] Until these feedbacks are understood and incorporated into the models, estimating global temperature increases accurately is difficult.

Clouds are the most uncertain feedback in the climate models, according to climate modelers, yet they have the potential to amplify or diminish the warming significantly.[6] All clouds act, to some extent, as "reflecting blankets," simultaneously cooling the earth by reflecting incoming sunlight back into space and warming the earth by preventing the earth's heat from escaping. In general, however, low cloud coverage or depth produces a net cooling effect, while high clouds have more of a warming effect. According to scientists at GISS, some models show an increase in high clouds with doubled carbon dioxide and thus estimate more warming. However, clouds are often handled simply by GCMs. For

[5]As another example of limitations in GCMs, EPA noted that they do not include the possible effects of biogenic feedbacks.

[6]D. Lashof, The Dynamic Greenhouse: Feedback Processes That May Influence Future Concentrations of Atmospheric Trace Gases and Climatic Change, EPA (Washington, D.C.: Jan. 4, 1989), p. 7.

example, in the GFDL model, if 90 percent or more humidity is estimated in a grid box, it has cloud coverage. Thus, there are large uncertainties about how clouds will really behave, and the different modeling groups that we spoke with put little confidence in their models' ability to account for cloud feedback.

Exclusion of the Deep Ocean

Ocean processes can affect climate change from increases in greenhouse gases in several ways. For example, the ocean's absorption of carbon dioxide would lower the amount retained in the atmosphere and, thus, lessen the extent of greenhouse warming. In addition, possible changes in ocean currents would alter the global distribution of heat. Until recently, atmospheric GCMS included only simplified representations of oceans in which oceans were assumed to have no currents, to instantaneously mix with the upper ocean, and to do little more than absorb and conduct heat. Modelers are now attempting to join an independent ocean circulation model with one for the atmosphere. In recent years, more complex representations of the oceans have been developed by GFDL, the National Center for Atmospheric Research (NCAR), and OSU. A recent NCAR model, for example, considers ocean circulation and estimates a global warming of only 1.6 degrees Celsius from a doubling of greenhouse gases.

According to scientists at GFDL, GISS, and NCAR, fully coupled ocean-atmosphere models would take into account heat transport and other interactions throughout the ocean, rather than just at the surface. Including these interactions is important because the ocean's huge heat-absorption capacity could potentially slow the effect of atmospheric warming. A coupled ocean-atmosphere model run by OSU in 1984 estimated that there would be a lag of 50 years or more before the temperature increase from greenhouse gases was realized.[7] In addition, scientists at GFDL estimated that there would be a lag in the warming at the South Pole because of effects calculated by their model's deep ocean component. Specifically, because of the upwelling of cold, deep ocean water, the surface waters around Antarctica would fail to warm for several hundred years, keeping the sea surface temperature at Antarctica cooler than estimated by previous models.

[7] J. Norris, "To Predict Pace and Extent of Global Change Better Computer Models Are Needed," NSF News (Feb. 1989), p. 5.

Implications of the Models' Limitations

The limitations in GCMs have hindered scientists' ability to use the models' estimates for research on the effects of global warming. The models' coarse resolution hinders researchers' ability to study regional effects, and the crude parameterization of key climate processes limits the precision of the warming estimates. Improved estimates are needed to help policymakers at the federal, state, and local levels develop better strategies for adapting to climate change.

One of the most certain effects of global warming is a rise in sea level, but a reliable, accurate estimate of the possible rate of potential increase is not available. Currently, the best estimate of the rise in sea level by the year 2050 is about 30 centimeters, but the uncertainties surrounding this estimate allow the possibility of a rise of as much as 70 centimeters, or perhaps none at all.[8] Global warming contributes to this rise in sea level in three primary ways—thermal expansion of the oceans, melting of mountain glaciers, and melting or sliding of ice sheets into the oceans. Estimates of potential thermal expansion are only as good as the estimates for ocean circulation and the potential average surface warming of the earth, and are, therefore, affected by the models' limitations. In addition, because ocean currents and ice sheets are not incorporated well in the models, the melting threshold of these sheets is relatively unknown. Finally, without regional representation of warming trends, it is difficult to estimate how much mountain glacier or ice melting will occur.

The extent of the rise in sea level is also uncertain because there is considerable uncertainty about when to expect the increased warming and the rate at which the warming will occur. Analysis of the rise in sea level needs to include the timing of the warming because that will affect how much the oceans expand and whether ice sheets and glaciers break up. However, the precise timing of climate change is still unknown because of uncertainties surrounding future releases of greenhouse gases and the limitations of the climate models.

Federal, state, and local officials need accurate estimates of the rise in sea level and of its timing to evaluate individual projects in coastal zones. Parties that could be affected by a rise in sea level need to determine whether the impacts will require changes in their operations and how much these changes will cost. EPA estimates that it may cost between $73 billion and $111 billion (cumulative capital costs in 1985

[8]M.F. Meier, "Reduced Rise in Sea Level," Nature, vol. 343 (Jan. 11, 1990), pp. 115-116.

dollars) to protect developed coastal areas in the United States against inundation and erosion from a 1-meter rise in sea level.

For example, it was reported that Charleston, South Carolina, is designing a new storm drainage system that will cost about $4.8 million, and what the capacity of the system should be depends in part on what the rise in sea level will be.[9] For an additional $270,000, larger pipes could be installed to accommodate the 30-centimeter rise in sea level expected by 2025. Without the larger storm runoff system, and assuming the 30-centimeter increase, the system would require a $2.4-million retrofit. The city has to decide whether to invest in a larger storm runoff system in anticipation of a future rise in sea level, or to choose the less expensive system that would meet its needs if there is no significant rise.

On the federal level, several agencies need estimates of the rise in sea level to effectively implement their programs. The Army Corps of Engineers will need to consider the rise in sea level before developing future coastal projects, such as beach restoration, which costs millions of dollars. In addition, the Federal Emergency Management Agency (FEMA) provides federal flood insurance to coastal properties worth billions of dollars. FEMA needs to anticipate the rise in sea level in order to adjust its policies and insurance rates.

Until GCMs are improved, the models' results will be useful only as "scenario" climate variables—numbers used to build possible scenarios of future climate, upon which impact analyses can be based. Improved estimates from GCMs are needed to aid policymakers in developing effective adaptation strategies for climate change.

Requirements to Improve GCMs

The limitations in GCMs—coarse resolution and exclusion of key climate processes—are expected to decrease over the next 5 to 10 years, according to scientists we spoke with. The rate of improvement depends on additional research to better understand climate change, increased computer capacity, and additional observational data. The scientists we spoke with generally agree that improvements in the models are likely and estimates should improve with time.

[9] J.G. Titus, "Greenhouse Effect, Sea Level Rise, and Coastal Zone Management," Coastal Zone Management Journal, vol. 14 (1986), pp. 163-164.

Research Needs

To improve their understanding of climate change, according to scientists, science will need to advance in many research areas, such as climate modeling, biological modeling, atmospheric chemistry, and oceanography. Furthermore, additional scientists will be needed to ensure that research in these areas advances.

Graduate students need to be attracted to climate change research to ensure that an adequate number of scientists will be working on the problem in the coming decades, according to the Director of GISS. He emphasized that a variety of specialists—including field observation gatherers, modelers of hydrologic cycles, and atmospheric scientists—are needed to gain a better understanding of these issues.

Observational Data

Most scientists we spoke with emphasized the need for extensive, long-term observational programs to provide data on climate systems. These climate data are needed to improve the climate processes included in the models and to evaluate the results of the models by comparing them to the current climate. For instance, better ocean models require more measurements of ocean processes, and improved forecasts of regional vegetation require better data on its distribution and changes. Both satellite and ground-based data on climate change need to be gathered for decades to gain a continuous record. Climate processes represented in GCMs cannot be evaluated without observational data and studies of these processes in the present climate.

For example, many modelers have been working on improving the representation of clouds in GCMs, one of the weakest components of the models. To evaluate their estimates of cloud behavior, modelers need to compare their modeled clouds with observations of clouds in the present climate. A recent observational program, funded by NASA and NOAA, the Earth Radiation Budget Experiment (ERBE), has been collecting satellite data on the radiative balance of the earth.[10] Until ERBE, observations around the globe were insufficient to determine whether clouds cooled or warmed the earth. Data obtained from the ERBE program have given scientists a basis to begin improving their modeled clouds.

[10]The radiative balance of the earth is the balance between radiation gained from the sun and radiation lost through re-radiation from the earth. The balance between radiation lost and gained depends upon the concentration of greenhouse gases in the atmosphere.

Similarly, NASA has studied the feasibility of implementing a satellite program for measuring tropical rainfall—the Tropical Rainfall Measuring Mission (TRMM). Atmospheric circulation is in large part determined by the energy released by precipitation; consequently, an accurate measurement of global precipitation is essential for understanding how the global climate system operates. The amount of precipitation falling on the earth at many specific locations may be 2 or 3 times more or less than current estimates, according to NASA scientists. TRMM would help fill that informational gap and increase scientists' understanding of precipitation patterns and of how to simulate them in climate models and how to estimate changes in precipitation in response to other climate changes. The planned TRMM project will be undertaken jointly by the United States and Japan, costing each nation about $150 million.[11]

Computer Resources

The development of models and improvements in regional estimates of climate change are also affected by computing power. The largest supercomputers available are saturated by today's GCMs, despite their vast simplifications. Some improvements in models, such as increased resolution and ocean-atmosphere coupling, cannot be made without increased computing power.

Scientists are hampered in their attempt to improve the models' resolution because smaller-scale models require more computing time and capacity and, thus, are becoming more expensive. To reduce grid sizes by half would require 8 times the number of calculations on a supercomputer and 16 times the number of calculations if vertical resolution were made correspondingly finer.

In addition, running completely coupled atmospheric and oceanic models for a sufficient number of simulated years to adequately describe climate change is not yet possible, in part because there is no computer powerful enough to deal with the necessary data. Some researchers believe that massively parallel supercomputers are needed to improve the models' estimates.

Two modeling groups we met with, GFDL and NCAR, are planning to obtain more current supercomputers for modeling. Expected benefits from their updated computers include improved resolution in GCMs, more realistic atmosphere-ocean climate models, better treatment of clouds and

[11] According to NASA, this project is in the planning stage. A start-up date has not been determined.

chemistry, better assessments of regional climate change, and better explanation of observational trends. Nonetheless, the modelers at GFDL expect to saturate the new supercomputers quickly, and significant computational compromises will still be necessary to run GCMs. The Director of GFDL explained that although an increase in computing power will give modelers the opportunity to research new pieces of the climate change problem, the climate system's overall complexity is greater than could be handled by any supercomputer currently being planned.

GAO's Observations

Although estimates from GCMs are now limited by computer resources, data, and scientists' understanding of climate processes, these estimates indicate that greenhouse gases will increase the average global temperature over the next century. The extent, magnitude, and timing of these changes are uncertain, but are the subject of current and planned research. With better estimates, policymakers and scientists will be able to improve their understanding of the impact of climate change on diverse areas, including agricultural productivity, water resources, human health, and the environment. Such information will assist policymakers in developing strategies to prepare for, prevent, or limit the effects that are likely to occur with climate change.

Agencies' Comments

EPA noted several limitations in this chapter. First, EPA noted that the report surveys what is known about the physical climate but not what is known about the response of living organisms to climate change. EPA pointed out that as the earth's temperature warms, biogenic feedbacks can be triggered that may affect the warming. For example, as global temperatures increase, tundra areas could melt, releasing trapped methane, which in turn would enhance the greenhouse effect. In addition, EPA noted that information on the response of ecosystems to climate change will be valuable in developing strategies for adapting to environmental changes induced by a changing climate.

We agree with EPA on the importance of understanding the effect of climate change not only on ecosystems but also on other important areas, such as agriculture, water resources, and human health. But before addressing these issues, we believed it was important to examine first the causes of the greenhouse effect and estimates of climate change, which we focused on in this initial effort.

NASA noted that some information presented in this chapter is oversimplified in the executive summary, specifically the meaning of the use of an "equivalent" doubling of carbon dioxide by modelers. In addition, NASA said that we omitted discussing that global ocean circulation models are more poorly developed than atmospheric circulation models. We agree with NASA that this is an important issue. We mentioned ocean circulation models in our discussion of the limitations of GCMs. Our purpose, however, was to examine atmospheric GCMs, not ocean models.

NOAA commented that this report represents a summary of recent, but not current, findings of individual groups rather than a true scientific consensus on global warming.[12] Further, NOAA noted that a forthcoming IPCC assessment will provide a more up-to-date evaluation of global change than this report. In particular, NOAA noted that our temperature ranges (5 to 8 degrees Fahrenheit) for global warming were higher than the current best estimates (3 to 8 degrees Fahrenheit). Similarly, DOE noted that the estimates we reported could include the results of more recent studies. To reflect these more recent estimates, we have included information from IPCC's executive summary where appropriate. Furthermore, we added estimates from a model by the United Kingdom Meteorological Office and more recent model results from NCAR's model, thereby expanding the temperature range cited to 3 to 9 degrees Fahrenheit.

NOAA further stated that the report assumes that effects of global warming will occur and that they will be negative, even though there is uncertainty in many areas. NOAA also asserted that new findings suggest that future changes may not be as severe as indicated. DOE also commented that the report should discuss the potential for beneficial impacts of climate change. This report examines only one potential impact—a rise in sea level—as an example of the implications of limitations in GCMs. We used this example because experts told us that it was one of the most certain effects. We carefully pointed out that estimates of a rise in sea level are uncertain. We have modified our reported estimate of the extent of the expected rise in sea level to about 30 centimeters to reflect more recent findings.

DOE stated that the executive summary's discussion of chapter 3 would be strengthened if estimates of the effects of greenhouse gases on past and current climates were added. We did not include such information in this chapter or the executive summary's discussion of this chapter because we discuss it in chapter 2.

[12] We were surprised by this comment, since previous comments from NOAA scientists we interviewed described the report as well written and thoughtful, and as doing a good job of capturing the mainstream of scientific thought.

Policy Framework to Address Global Climate Change

Depending on its extent, magnitude, and timing, global warming could have a profound effect on many aspects of everyday life. While many of global warming's possible consequences may not manifest themselves until well into the next century, policymakers are faced with examining how best to respond now as well as in the long term.

Policymakers face several challenges in preparing for global warming. First, their responses need to take into consideration the global scope of the problem: All nations emit greenhouse gases, and all will experience the impacts. Second, the scientific uncertainties make it difficult to ascertain the correct response because the climate may change more or less than anticipated and may even change in unanticipated ways. Furthermore, the regional effects are projected to be uneven. Third, and perhaps more importantly, policymakers must weigh the risk of more adverse impacts by delaying action while they wait for additional scientific information against prematurely taking costly actions that may prove unwarranted.

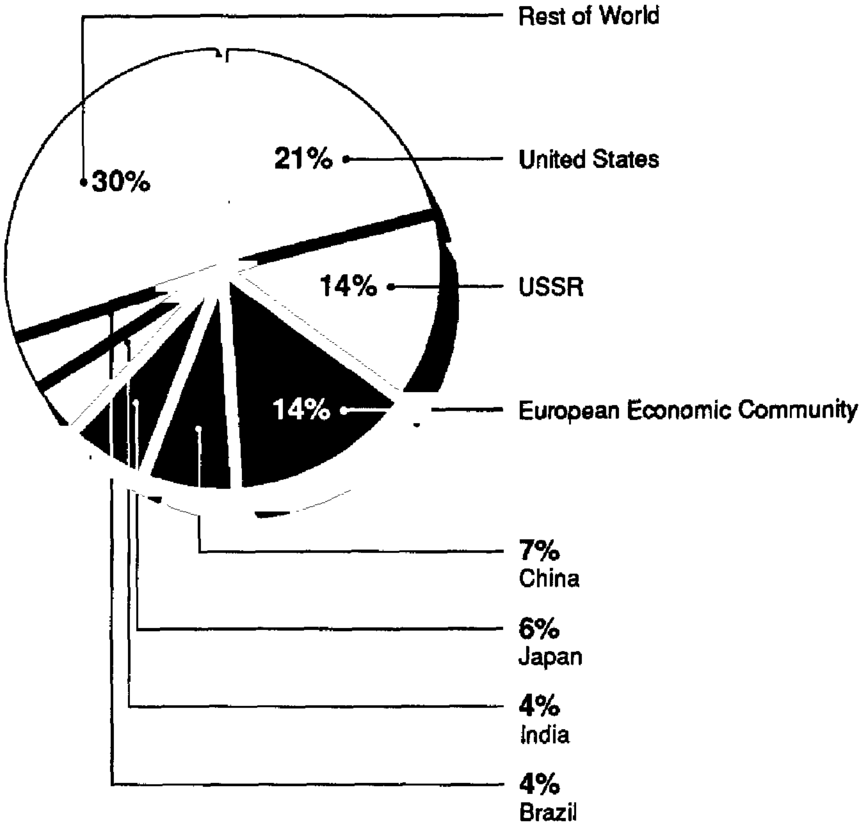
Nonetheless, we found that some environmental and industrial organizations support taking actions now to reduce greenhouse gas emissions rather than waiting until the earth is committed to potentially harmful warming. They reason that actions now will have benefits in addition to reducing greenhouse gases. Reductions of some greenhouse gases, such as CFCs, are in fact already underway.

Nature of the Problem

Global warming and its potential impacts on society and the environment are international problems whose exact nature is unknown because of the scientific uncertainties discussed in chapters 2 and 3. Since greenhouse gases have already been released, we may be committed to a 1- or 2-degree Celsius increase in the average global temperature. Concern about accelerated global climate change has focused national and international attention on the potential for reducing emissions from man-made sources and adapting to the possible impacts of global climate change.

Any comprehensive, long-term solution will require the cooperation of many countries and reductions in many sources. All countries contribute to greenhouse gas emissions and share some responsibility for their continued growth. As shown in figure 4.1, the United States and Western Europe account for about 35 percent of the greenhouse gas emissions. Since the early 1970s, however, their emissions have generally remained stable, while the emissions of developing countries have steadily increased. Because the United States is a major contributor of greenhouse gas emissions, some believe it should be a leader in developing responses to the problem, including assisting developing countries in limiting their contributions to greenhouse gas emissions.

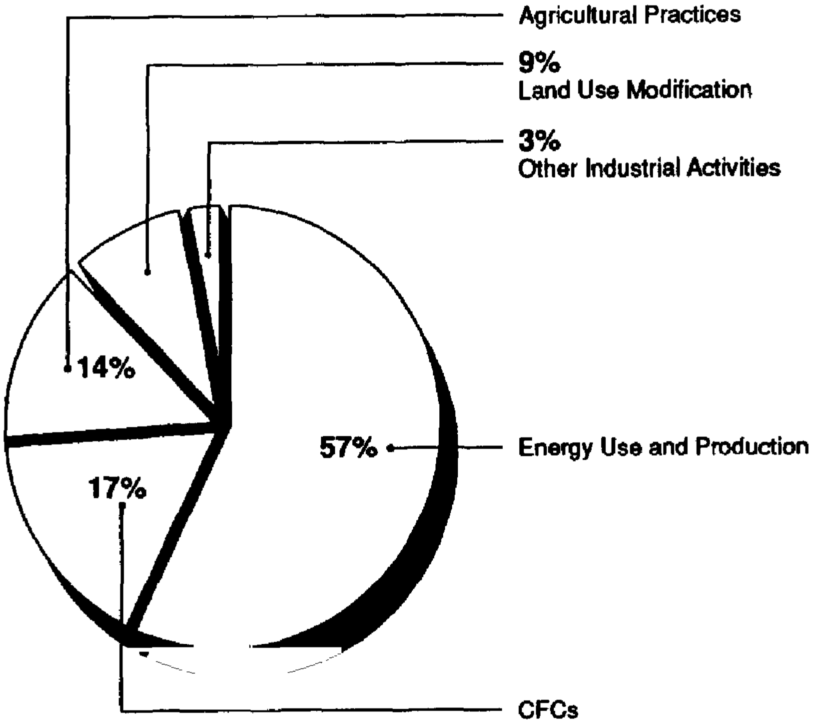
Figure 4.1: Regional Contributions to the Greenhouse Effect During the 1980s



Source "Policy Options for Stabilizing Global Climate," EPA, briefing paper (March 1989), p. 5.

Industrial and agricultural activities by these nations are responsible for the increases in greenhouse gases. As shown in figure 4.2, these activities include energy production and use, industrial activities (including the use of CFCs), agricultural practices, and changes in land use (including deforestation).

Figure 4.2: Activities Contributing to Global Warming



Source: Lashof and Tirpak, Policy Options for Stabilizing Global Climate, p. 55.

International Panel on Global Warming Established

To develop an international response to the threat of global warming, the United States and over 35 other nations and international organizations are participating in IPCC. The panel was established in 1988 by the World Meteorological Organization and the United Nations Environment Programme. The panel's goals are to (1) review and assess the science relevant to climate change, (2) assess the possible environmental and socioeconomic impacts of climate change, and (3) identify potential response strategies. To address these goals, the panel established three working groups in 1988. The United States chairs the working group addressing response strategies and has representatives in the two other working groups. These working groups were scheduled to complete their work and report their results in June 1990. IPCC had plans to complete its overall report by late August or early September 1990.

Legislation Proposed to Address Global Warming

The threat of global warming has become the subject of policy debate in the United States. The 101st Congress has introduced over 20 bills on global warming. These bills generally propose measures to reduce greenhouse gas emissions and/or studies to examine responses to the effects of global warming. Several bills define federal agencies' responsibilities for dealing with these issues. In addition, the Congress passed the Global Climate Protection Act of 1987, which, among other things, requires that the President, through EPA, develop and propose to the Congress a coordinated national policy on global climate change. The Congress further requested that EPA report on the potential effects of global climate change and on policies to reduce the emission of greenhouse gases.[1] In addition, the 101st Congress is considering the reauthorization of the Clean Air Act, which could have implications for reducing greenhouse gas emissions, particularly CFCs.

Actions to Respond to Global Warming

The scientific uncertainties surrounding possible global warming make it difficult for policymakers to determine the correct responses to it. Potential strategies for responding to climate change fall into two categories. Adaptation strategies adjust the environment or our ways of using it to reduce the consequences of a changing climate. Limitation strategies control or stop the growth of greenhouse gas concentrations in the atmosphere and limit climate change. These two responses are complementary, not mutually exclusive. Because past and current emissions probably make a warming of several degrees Celsius unavoidable, some adaptation will be necessary. On the other hand, slowing the rate of global warming would make it easier for society to adapt. While limitation strategies require worldwide cooperation, adapting to the consequences of global warming do not.

Although control or abatement of greenhouse gas emissions is the most certain way of minimizing or avoiding climate change, it seems unlikely that this will happen before some greenhouse warming occurs. Several areas may be particularly affected by climate change. For example, increased temperatures and changes in precipitation could result in rising sea levels, which might erode or inundate coastal areas; dieback of forests; changes in agricultural productivity; scarcity of water resources; increased energy demand; further air pollution; and health problems.

[1] Smith and Tirpak, Potential Effects of Global Climate Change on the United States, and Lashof and Tirpak, Policy Options for Stabilizing Global Climate.

Adaptive Strategies

A wide range of adaptive responses to global warming can be pursued: avoiding development in unprotected coastal areas, developing more heat-resistant strains of crops, planting heat- and drought-resistant trees, using water resources more efficiently, and establishing corridors for plant and wildlife migration. Because localities will differ in how they are affected by climate changes, adaptive measures can be pursued at the local, state, and national levels. Private citizens and companies can relocate or modify their operations. Communities and states can undertake public works or enact planning measures. National governments can support all of these activities. Above all, adaptive measures will require flexibility in program management to respond to unforeseen climate changes.

Limitation Strategies

Regardless of the scientific uncertainties, measures to limit current greenhouse gas emissions would decrease the magnitude and the speed of global warming. In developing priorities on limiting emissions of greenhouse gases, policymakers need to consider the relative importance of the gases and the practicability of controlling them. As discussed in chapter 2, carbon dioxide is responsible for about half of the potential for increase in atmospheric temperature. As a result, current discussions at the national and the international level generally center on how to control carbon dioxide. Methods being discussed include increased energy efficiency, which is considered by many groups we spoke with to be the most practical solution; increased use of renewable energy sources; limited deforestation; and increased use of nuclear energy, which is considered a solution more viable in the distant future than in the near future.

Energy Efficiency

An effective strategy to slow global warming will involve moving away from reliance on fossil fuels, which currently provide over 75 percent of the world's energy. This adjustment can be achieved by using energy more efficiently, which reduces the amount of fuels that must be burned, or by replacing fossil fuels with alternative energy sources, such as solar or nuclear power.

According to Worldwatch Institute, improved energy efficiency has the immediate potential to cut fossil fuel use at a rate of at least 2 percent annually in industrial countries, with a commensurate reduction in carbon dioxide emissions. Energy-efficient actions include improving the efficiency of devices that use electricity—such as appliances, lighting devices, and buildings—and improving energy efficiency in the transportation sector.[2]

Currently, 64 percent of the world's electricity is produced by using fossil fuels (chiefly coal), accounting for 27 percent of global carbon emissions from fossil fuels (1.5 billion tons annually). Many uses of electricity can become more efficient. For example, with current technologies, electric motors can be made at least 40 percent more efficient, and refrigerators 75 percent more efficient.

The potential of energy efficiency to reduce greenhouse gas emissions is also evident in transportation. Transportation emissions worldwide add more than 700 million tons of carbon to the atmosphere annually. Increasing the fuel efficiency of cars would lower carbon emissions. For example, one report estimates that doubling the fuel efficiency of a typical car to 50 miles per gallon could reduce its carbon emissions by half, while lowering the annual gasoline fuel bill by almost $400.[3]

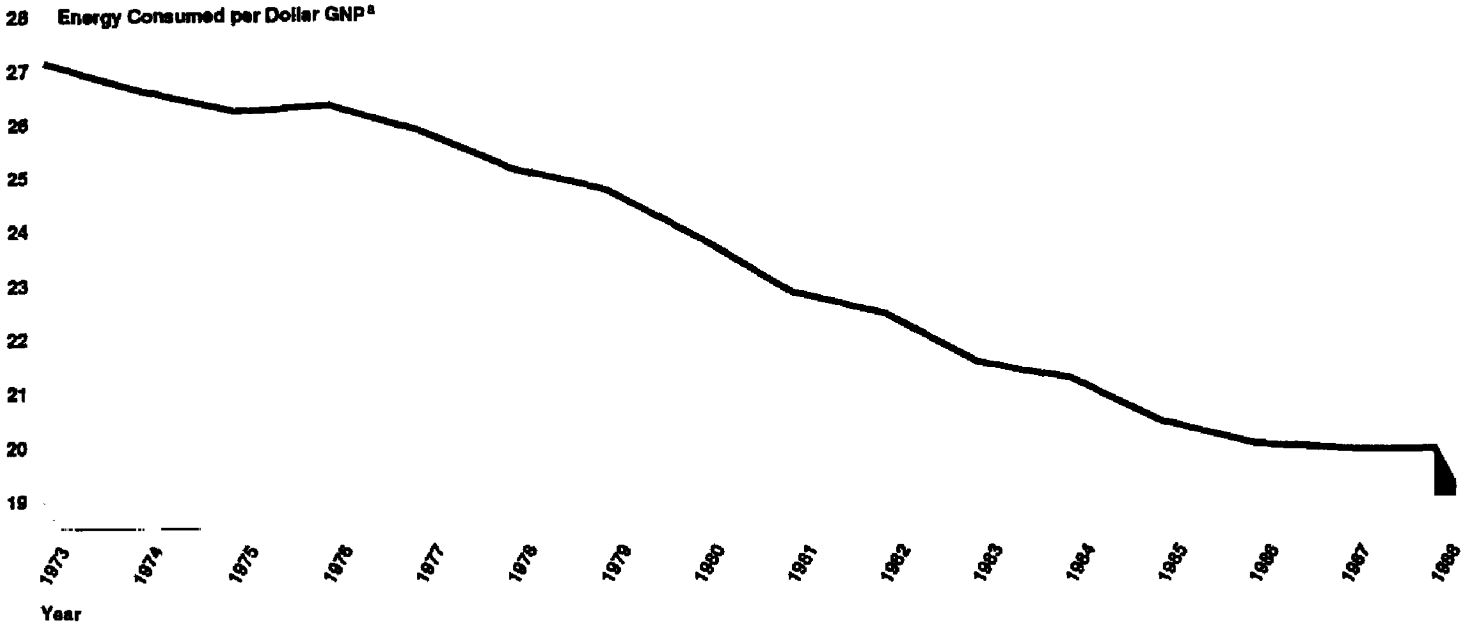
The United States realized gains in energy efficiency during the 1970s and 1980s (see fig. 4.3) without drastic or abrupt changes in lifestyle. Some environmental groups believe that the United States can achieve even greater efficiency gains. Compared with Japan, for example, the United States consumed roughly 60 percent more energy per dollar of national income.[4]

[2]C. Flavin, "Slowing Global Warming: A Worldwide Strategy" (Washington, D.C.: Worldwatch Institute, Oct. 1989), p. 34.

[3]C. Flavin and A. Durning, "Building on Success. The Age of Energy Efficiency" (Washington, D.C.: Worldwatch Institute, Mar. 1988), p. 56.

[4]According to the International Energy Agency, in 1987 the United States' energy use was 0.31 (total final consumption in tons of oil equivalent per thousand dollars of gross domestic product) compared with Japan's use of 0.19. International Energy Agency, "Energy Policies and Programmes of IEA Countries: 1988 Review," (Paris: 1989).

Figure 4.3: Gains in Energy Efficiency in the United States From 1973 to 1988



[a]Energy consumed is measured in thousand British thermal units. Gross national product (GNP) is measured in 1982 constant dollars.

Source: DOE, Monthly Energy Review (May 1989), p. 18.

However, several obstacles stand in the way of increasing energy efficiency, according to some of the groups we interviewed. These obstacles include the relatively low cost of some fossil fuel energy, such as gasoline, in the United States, compared with costs in other countries; choices by energy consumers that focus on short-term costs; and relatively low levels of federal funding for research and development.

According to some environmental groups, the price of energy does not reflect its true social cost. They note that energy prices do not reflect the cost to society associated with polluting emissions from fossil fuels. These groups favor taxes on fossil fuels to bring prices closer to the social cost. Additionally, they point out that the United States' gasoline prices are considerably lower than those in the rest of the industrialized world.

Advocates of energy conservation also point to the choices made by energy consumers that do not take into consideration total long-term costs. For example, consumers may buy less energy-efficient appliances because their purchase prices are lower, even when the life-cycle costs of higher-priced, energy-efficient appliances are lower.[5] Consumers may have insufficient information on technological advances and may put economic considerations first in making choices about energy efficiency.

Similarly, businesses may fail to invest in energy conservation projects with relatively high financial returns in the long term. This failure to invest may be caused by policies and institutions that encourage energy demand. For example, utilities have been regulated in a way that makes demand growth attractive for investors and, hence, makes sales attractive to utility managers and investors.

These obstacles may be addressed by a variety of programs to promote conservation. For example, electric utility companies have promoted programs to increase consumers' efficient use of energy, such as offering rebates for using energy-efficient appliances, developing home weatherization programs, and disseminating information to consumers on energy-efficient choices.

Finally, the steady decrease during the 1980s in federal funds for research and development of energy-efficient technologies may be another obstacle to improved energy efficiency. DOE's funding for energy conservation research and development dropped from $325 million in 1979 to $129 million in 1988.[6]

Renewable Energy Sources

Replacing fossil fuels with increased use of renewable energy sources—such as solar cells (photovoltaics), solar thermal energy, wind, geothermal energy, and biomass—would also reduce the emission of greenhouse gases.[7] In 1988, renewable energy provided about 9 percent of the total energy used in the United States. By the year 2000, one report estimates that it may provide almost 15 percent of the United States' total

[5]Life-cycle costs include the purchase price plus operating and maintenance costs expressed in constant dollars over the lifetime of the appliance, less its scrap value at the end of its lifetime.

[6]These amounts are expressed in 1982 constant dollars.

[7]Solar and wind technologies convert these resources into usable high-temperature heat or electricity. Geothermal energy comes from the heat contained in underground rocks and fluids. Biomass energy is produced from the combustion of organic materials, such as plants. Although the combustion of biomass produces carbon dioxide, the regrowth of biomass to replace what is harvested absorbs carbon dioxide from the atmosphere. As a result, there is no net increase in carbon dioxide.

projected energy needs, displacing over 500 million tons of carbon dioxide.[8]

Renewable energy, which is perceived to have a benign effect on the environment, is used to produce heat and electricity as described in the following examples.[9]

- Photovoltaic cells provide electricity to consumer products, such as calculators and watches, and to remote locations that have no access to electricity. It was reported in 1989 that U.S.-manufactured solar cells provide approximately 30 megawatts of electrical capacity.[10] As of 1989, there were at least 1.2 million buildings in the United States that incorporated some aspect of solar building design, such as solar hot water heaters. Solar thermal power is estimated to have produced about 500 million kilowatt-hours of electricity in 1989.[11]
- In the United States, wind-powered turbines generate approximately 1.8 billion kilowatt-hours of electricity annually.
- Geothermal energy is currently used by the United States and several other countries to generate direct heat and electricity. In 1988, geothermal power plants in the United States produced about 20.9 billion kilowatt-hours of electricity.
- Residential wood burning made up about 40 percent of the total wood energy used in 1988. Biomass electricity plants that burn sugar cane residues provided 58 percent and 33 percent of all electricity generated on the Hawaiian islands of Kauai and Hawaii, respectively, in 1985.

The high cost of most renewable energy sources, compared with the cost of fossil fuel sources, is considered an obstacle to their increased use. For example, according to the Council for Renewable Energy Education, electricity from coal-fired power plants costs less (6.8 cents per kilowatt-hour) than electricity generated from solar thermal sources (10 cents per kilowatt-hour), biomass (8 cents per kilowatt-hour), and wind

[8]N. Rader, Power Surge: The Status and Near-Term Potential of Renewable Energy Technologies (Washington, D.C.: Public Citizen, May 1989), pp. II-2 and III-1.

[9]EPA has commented that the benign effect of renewable energy is not simply a perception. While the use of renewable energy sources does have environmental impacts, they tend to be far less serious, more localized, and often easier to address than those caused by the use of fossil fuels.

[10]Rader, Power Surge, p. II-36.

[11]Solar thermal electric power plants basically use mirrors to focus sunlight to heat a fluid that is then used to produce steam to run a conventional electric turbine.

(6.9 cents per kilowatt-hour). On the other hand, they estimate that electricity from geothermal sources and hydropower is cheaper (6.5 and 4.5 cents per kilowatt- hour, respectively).

Furthermore, each renewable energy source has specific disadvantages that may pose obstacles to its increased use. For example, photovoltaic power stations require large land areas, currently about 10 acres per megawatt.[12] Wind-powered turbines provide intermittent power because they generate electricity only when the wind blows. Geological stress associated with drilling geothermal projects may contribute to land subsidence and sink holes. Residential wood burning creates air pollution problems, such as the emission of particulates because of incomplete combustion.

EPA has pointed out that these limitations may have solutions or may not exist in all regions of the country. For example, there is abundant land in the southwest United States for solar energy installations, and the geothermal industry has developed methods of extracting energy to limit geothermal stress. Furthermore, EPA has noted that additional research for renewable energy would lead to greater implementation of these techniques.

Reforestation

According to EPA, changes in land use—including deforestation, the burning or clearing of forest land for other uses, such as agriculture—are responsible for about 10 percent of the greenhouse gas emissions contributing to global warming.[13] Reforestation of these lands, on the other hand, absorbs carbon dioxide from the atmosphere and buys time for other policy actions to be implemented. Reforestation could be implemented by such actions as swapping assumptions of debt with developing countries for environmentally sound programs like reforestation and, in the United States, using USDA's Conservation Reserve Program for the reforestation of highly erodible cropland.[14]

[12]According to DOE, however, photovoltaic power plants use nearly the same amount of land as conventional plants when operations, construction, extraction, and transportation are taken into account.

[13]Burning forest land releases stored carbon dioxide from the trees. Clearing forest land removes trees that would absorb carbon dioxide from the atmosphere through photosynthesis.

[14]The Conservation Reserve Program assists farmers in converting erodible and environmentally sensitive cropland into forests or grassland. Some organizations that we spoke with believe this program is the logical place to begin a national reforestation plan to offset carbon dioxide emissions.

One obstacle to reforestation is resistance by developing countries. Many developing countries see few alternatives to clearing forest as a way to earn hard currency, to spur regional economic development, and to open new areas for settlement. For example, in Brazil much forest land has been cleared because government subsidies encourage cattle ranching, even though ranching erodes pasture land and, consequently, the projects are abandoned within a few years.

Other obstacles to reforestation include the extensive area required for planting and the question of who will pay for the reforestation. For example, a DOE researcher estimated that the United States would need to plant trees on an area 50 percent larger than its total land area to offset its contribution to carbon dioxide emissions.[15] He concluded that the United States cannot absorb all its carbon dioxide with a reforestation program alone and that reforestation should be viewed as a short-term measure that allows time to find alternatives to fossil fuels.

Nuclear Energy

Nuclear energy is a controversial solution to global warming. Proponents of nuclear energy point out that nuclear power plants can decrease the greenhouse effect by substituting nuclear power for fossil fuels to generate electricity. According to one report, nuclear power plants reduced the United States' emissions from burning fossil fuels in 1987 by almost 9 percent and global emissions by over 7 percent.[16]

Opponents of nuclear energy cite costs, problems in disposing of radioactive waste, and the lack of acceptance by the public as the main obstacles to the increased use of nuclear energy. Advocates of nuclear energy, on the other hand, believe these problems will be dealt with by the next generation of nuclear technology, which is now under research and development. This new technology, however, is not expected to be in production before the year 2010. Therefore, advocates view nuclear energy as a longer-term strategy for responding to global warming.[17]

[15]"The Role of U.S. Forestry in Addressing the CO_2 Greenhouse Problem," remarks by Gregg Marland before the Senate Committee on Energy and Natural Resources, Sept. 19, 1988, pp. 1-2.

[16]U.S. Council for Energy Awareness, Greenhouse Fact Sheet, undated.

[17]DOE has noted that nuclear power is currently considered a viable option in many countries. In the United States, DOE anticipates that new reactor options may be available as early as 1995 to resolve many technological and operational concerns.

Strategies to Control Greenhouse Gases Other Than Carbon Dioxide

Although they are currently responsible for about half the potential for temperature increase, greenhouse gases other than carbon dioxide, when taken together, may surpass carbon dioxide as the primary contributors to potential warming within the next decade (see ch. 2). Strategies to reduce energy consumption and production will also reduce the emission of other greenhouse gases, such as methane and nitrous oxide, in addition to carbon dioxide. Other policies can be targeted to specific gases.

For example, landfills are a small but potentially controllable source of methane. Waste disposal in landfills and open dumps generates methane when organic material decomposes. These emissions can be reduced by methane recovery systems and by the minimization of wastes.

EPA commented that reducing methane from landfills can have a relatively large impact, since only a 10- to 20-percent reduction in methane emissions is required to stabilize atmospheric concentrations. Other areas EPA mentioned for reducing emissions include coal mining activities, animal wastes, and livestock.

Several agricultural activities are sources of methane and nitrous oxide emissions: digestive processes in domestic animals such as sheep and cattle, rice cultivation, and the use of nitrogenous fertilizer. Several techniques—such as feed additives for cattle, changes in water management in rice production, and fertilizer coatings—have been identified for reducing methane and nitrous oxide emissions from these sources. According to EPA, however, these techniques require further research and demonstration before they can be implemented.

The production and use of CFCs will be limited by the Montreal Protocol, signed in 1987 by 24 dozen nations.[18] The United States ratified the protocol in April 1988. Under the protocol, the world's industrial nations agreed to halve production and consumption of CFCs in a decade, to periodically assess the protocol's control measures, and to make changes in

[18]The purpose of the Montreal Protocol on Substances That Deplete the Ozone Layer is to reduce CFCs because they destroy ozone in the upper atmosphere. In the lower atmosphere, however, CFCs act as a greenhouse gas, and the protocol, therefore, has the additional benefit of reducing greenhouse gas emissions.

the controls if necessary. In 1989, the United States and several European countries agreed to completely eliminate CFCs by 2000.[19] United States legislators have added such language to the proposed reauthorization of the Clean Air Act.

U.S. Options to Reduce Greenhouse Gas Emissions

The federal government can use several methods to encourage activities that reduce the emission of greenhouse gases. As mentioned earlier, energy pricing to promote conservation, further research and development of energy-efficient technologies, and information programs for energy consumers would help to overcome some of the obstacles that hinder limiting the emission of greenhouse gases. In addition, the federal government already has several regulations and programs that affect greenhouse gas emissions, such as air pollution control laws, restrictions on the use of CFCs, regulation of investments and rates charged by utilities, and energy efficiency standards for automobiles and appliances. These programs were adopted for reasons unrelated to climate change, but could be modified to reduce greenhouse gas emissions even further.

Similarly, DOE has been tasked with developing a national energy strategy that could be specifically targeted to reduce greenhouse gas emissions. This strategy is to be completed by December 1990 for the President's consideration. The strategy will address global climate change within a comprehensive set of energy and other national goals. According to DOE, this plan is expected to serve as a blueprint for energy decisions, providing a choice of competitively priced, clean-energy supplies. The strategy will generate several energy policy options, illustrate how each option will be implemented at the program level, and indicate the program's funding requirements. Furthermore, the strategy is expected to contain specific recommendations on how to best balance concerns for energy, economic, and environmental requirements. DOE is developing models for the strategy that will project the impacts of various energy options on such issues as global warming.

In addition, the federal government needs to examine policies and programs that may inadvertently exacerbate the threat of global warming. For example, "scrubbers" may be used on electric power plants to reduce sulfur dioxide emissions and thereby limit acid rain. However,

[19]According to EPA, the protocol's impact on global climate is difficult to determine because (1) CFCs that are already in the atmosphere will remain there for about 100 years and (2) the effect on climate of substitutes for CFCs remains unknown. However, according to NOAA, these substitutes have much shorter lifespans, although their greenhouse potential is roughly the same as CFCs on a molecule-per-molecule basis.

scrubbers will increase carbon dioxide emissions by reducing the efficiency of power plants. Another policy, to reduce the production and use of CFCs as part of the Montreal Protocol agreement, could unintentionally increase the emissions of other greenhouse gases. Some substitutes for CFCs are less energy-efficient and, therefore, could result in increased carbon dioxide emissions.

Timing of Responses to Global Warming

Responses to global warming require a combination of immediate and long-term policies. For example, pricing and regulatory strategies may be effective in the short term, while government-supported research, development, and information programs may reduce greenhouse gas emissions in the long run. Actions now may be desirable for several reasons: Some actions cannot be implemented immediately for political and economic reasons once it is agreed they are needed, and concentrations of greenhouse gases will decline only gradually even after actions are implemented. Many organization officials that we spoke with support taking actions to reduce greenhouse gas emissions as soon as possible, rather than waiting until the earth is committed to potentially harmful warming. Furthermore, some organizations believe that actions in the near future should emphasize activities that have benefits in addition to reducing the emission of greenhouse gases.

If policymakers wait until the scientific uncertainties are reduced to respond to global warming, they risk committing the earth to even more warming. Once greenhouse gases have entered the atmosphere, they continue to affect the climate for decades. If all man-made emissions of carbon dioxide were eliminated now, it could take more than a century for the oceans to absorb enough carbon to reduce the atmospheric concentration of carbon dioxide even halfway toward its preindustrial value. With continued emissions, the time required to reduce excess concentrations by the same percentage increases even more. In addition, the climate's response to increases in greenhouse gases will be delayed because the ocean has a limited capacity for absorbing heat. Similarly, in response to decreases in greenhouse gases, temperatures will also cool more slowly because of the ocean's effect on climate.

Furthermore, policy development and implementation can be a lengthy process, particularly at the international level. For example, it took roughly a decade to develop and ratify the Montreal Protocol, and it may take even longer to reach agreement on other greenhouse gases, such as carbon dioxide, because the emission sources are more diverse and more countries are involved. In addition, implementing new technologies to reduce greenhouse gas emissions may take many years. For example, the next generation of nuclear energy technology, which is now under research and development, is not expected to be in production before the year 2010.

GAO's Observations

While ongoing and planned research is expected to help reduce some of the scientific uncertainties surrounding global climate change, quick fixes or easy answers are unlikely to emerge. Rather, research results are anticipated to continue pointing to the need for developing a comprehensive multinational, multidecade response strategy requiring a mix of near-term and long-term actions. In the near term, there is a growing recognition that certain actions can be justified because they have benefits in addition to reducing greenhouse gases. Reducing CFCs is an example of such an action already underway. Other actions, such as national efficiency standards for new appliances and similar improvements in energy efficiency, can have a near-term impact on reducing greenhouse gas emissions and, while progress has been made, more can be done. Also, the current situation in the Persian Gulf highlights the need to lessen dependence on foreign oil, and such measures as increasing the domestic use of renewable energy and energy-efficient technologies would help to achieve this goal. Other actions that make sense for other reasons and would help to reduce the effects of global warming include: promoting investments in energy-efficient technology to reduce energy costs and to meet the need for new generating capacity; and promoting waste reduction and recycling as alternatives to land disposal to address the high cost and environmental risks associated with traditional disposal methods.

Long-term solutions, however, raise broad issues that need to be considered on national and international levels in developing a comprehensive strategy to deal with global warming. For example, what acceptable alternatives to fossil fuel use are available to mitigate the projected global warming? How does the relatively low price of fossil fuel energy hinder increased energy efficiency and the use of alternative energy sources, such as solar energy? Will the public accept changes in lifestyle that may be necessary to decrease the emission of greenhouse gases? What is the potential, among so many nations, for achieving cooperation and coordinated action in a timely, effective manner? Will the industrialized world be able to work with and understand the special needs of developing countries in decreasing their fossil fuel emissions? Who can and will pay for policies to reduce greenhouse gas emissions? What actions, if any, need to be taken to adapt to a changing climate? What are the estimated costs of actions to reduce greenhouse gas emissions and adapt to climate change?

Despite such unresolved issues, our work suggests that actions such as increasing energy efficiency make sense for other reasons as well and should be implemented on both the national and the international level. More importantly, the threat of enhanced global warming in and of itself should serve as a catalyst to take action now.

Agencies' Comments

EPA agrees that there are many opportunities for reducing the emission of greenhouse gases at low costs, including opportunities to improve energy efficiency and to increase the use of renewable energy. However, EPA believed that this chapter omitted any reference to the international consensus on the urgent need for a framework convention on climate change and the United States' active role in that process. We agree that this is an important issue but excluded it from this report because the United States' international efforts concerning global warming were addressed in a recently issued GAO report, Global Warming: Administration Approach Cautious Pending Validation of Threat (GAO/NSIAD-90-63).

In addition, EPA felt that several issues had not been addressed in this chapter or needed further elaboration. Where appropriate, we have included additional information provided by EPA on (1) renewable energy sources and (2) strategies for reducing methane emissions.

NOAA stated that the report should include a chapter surveying estimates of the net economic costs associated with global warming and the economic costs of mitigation and adaptation strategies. Similarly, DOE believed that the report should discuss the costs and benefits of reducing emissions. We recognize that there are economic trade-offs that must be considered in any emissions reductions strategy. However, we found that certain actions, such as improvements in energy efficiency, have benefits in addition to reducing greenhouse gas emissions and could be implemented now.

DOE also said that our discussion of the potential for nuclear energy to reduce greenhouse gas emissions should be made more factual and consistent with the discussion of other technologies. We know of no information in the section that is not factual; however, we have expanded that discussion by adding DOE's specific comments.

NASA did not comment on this chapter.

DOE's Comments

The Under Secretary of Energy
Washington, DC 20585

March 29, 1990

Mr. Richard L. Hembra
Director
Environmental Protection Issues
United States General Accounting Office
Washington, DC 20548

Dear Mr. Hembra:

Thank you for the opportunity to comment on the draft General Accounting Office (GAO) Report: "Global Warming: Emission Reductions Possible While Scientific Uncertainties Being Resolved." Department of Energy comments are detailed in the two enclosures to this letter: Enclosure 1 - General Comments, and Enclosure 2 - Specific Comments.

Among the Department's primary concerns detailed in the enclosures are:

- a discussion of costs and benefits of emissions reductions should be included in this report to provide a more comprehensive analytical framework for a government strategy on climate change;
- the report would be strengthened if historical and more recent climate data were considered in the discussion of the effects of increased greenhouse gas concentrations on potential climate change;
- the results of models providing estimated changes to global average temperature in Table 3.1 and the accompanying discussion should be more complete, especially reflecting recent model results where cloud and ocean effects are more realistically simulated;
- the discussion of appropriate criteria for near-term actions to reduce greenhouse gas emissions should emphasize actions that also serve other policy objectives;
- the report should discuss the potential for beneficial impacts of climate change; and

2

- discussion of the potential for nuclear energy to reduce greenhouse gas emissions should be made more factual and consistent with the discussion of other technologies.

Your report indicated that it relies on data available through last October. Yet, as our comments note, some of the information contained in the report is already out of date because of recently-announced scientific discoveries.

Over the next six months, the Intergovernmental Panel on Climate Change (IPCC) will report on our scientific understanding of global climate change, the potential impacts of global climate change, and the economics of various response strategies to potential climate change. Given the IPCC activities, and other ongoing global climate change-related activity, it will be virtually impossible for this report to remain current. Publishing the report now, however, will convey the impression that it represents the best and most recent information that is available, an impressions that will not be correct.

We suggest that holding the report in draft over the next several months will allow GAO to incorporate more current scientific and economic research results. The Department of Energy would be pleased to work with you in such an endeavor, which we believe would result in a better, more useful report.

Also, enclosed is the Executive Summary of the Department's Atmospheric Radiation Measurement (ARM) Program Plan. The ARM Program should improve the treatment of cloud radiative forcing and feedbacks on the General Circulation Models.

We would be happy to discuss any of our comments with you.

Sincerely,

John C. Tuck

John C. Tuck

Enclosures

EPA's Comments

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

OFFICE OF
POLICY, PLANNING AND EVALUATION

APR 4 1990

Mr. Richard L. Hembra
Director, Environmental Protection Issues
Resources, Community, and Economic Development Division
General Accounting Office
Washington, D.C. 20548

Dear Mr. Hembra:

The Environmental Protection Agency (EPA) has reviewed the General Accounting Office (GAO) draft report entitled "Global Warming: Emission Reductions Possible While Scientific Uncertainties Being Resolved" (GAO/RCED-90-58). In accordance with Public Law 96-226, I am hereby providing the formal Agency response to the draft report.

The GAO draft report represents a substantial compilation of ongoing work, and achieves a well balanced view of the issues. In particular, it notes the current limitations in atmospheric modeling and the uncertainties about global climate change which follow from those limitations, while recognizing that actions can be taken now to begin reducing greenhouse gas emissions. The report also notes that many of the key policy questions are yet to be answered, such as whether individuals will be willing to change their lifestyles and how policies to reduce emissions will be funded.

While the report examines many of the current issues surrounding global warming, its usefulness could be strengthened by expanding it beyond a description of the current state of knowledge to describe the range of activities and progress being made to answer many of the questions it poses. Our understanding of the issues continues to improve rapidly, and a better sense of where the basic research and policy analysis is heading would improve key decision makers' abilities to provide proper guidance and support.

Some general comments on the content of the report follow; page-by-page comments are enclosed. In addition, the draft copies being returned to you under separate cover contain editorial comments in the margins.

2

Scope of the Report

A major limitation of the draft report is that it is limited to surveying what is known about the physical climate system. An equally important and challenging task is to survey what is known about the response of living systems to climate change. Biogenic feedbacks can be triggered as the earth's temperature warms. An example of such a feedback is methane release from tundra areas. With these feedbacks, some scientists estimate that average global temperatures could increase by 14 degrees Fahrenheit or more. While estimates are uncertain, such information is valuable because, as the draft acknowledges, climate will probably change to some degree. Policy makers require such information to balance costs and benefits of mitigation actions. In addition, this information will assist in developing adaptation strategies for environmental changes induced by a changing climate. The nearly complete omission of this important area of environmental response limits the overall usefulness of the report.

Modeling

The draft report emphasizes the use of general circulation models (GCMs), but does not recognize the usefulness of other modeling and analytical techniques, for example, radiative-convective models and chemistry models. Like GCMs, each analytical tool has its strengths, weaknesses and general domain of usefulness. Their omission from this draft creates the misleading impression that the only scientific means of studying the influence of increasing greenhouse gas concentrations is through the use of GCMs. Chapter 2 and the Executive Summary should be expanded to cover non-GCM analytical tools.

One limitation of the GCMs is that they do not include the possible effects of biogenic feedbacks, as discussed above. Another is their lack of credibility in predicting regional climate change. However, this does not mean that they should be abandoned for regional scale predictions. The results of modeled global climate change must make qualitative sense on smaller spatial scales. Some recent satellite radiation budget experiments have shown that there is an encouraging consistency between model and observed climate sensitivity. It is clear that progress in understanding climate change can come only from observations complementing modeling studies.

3

Estimates of Greenhouse Gas Emissions

The report correctly notes that estimates of future growth of greenhouse gas emissions are uncertain. However, it is important to note that projections are being made by the U.S. and other countries based on a number of assumptions about energy use, population growth, and economic productivity. These are the same type of projections (with the same uncertainties) that are made every day in planning processes, and this is being performed as part of the IPCC (Intergovernmental Panel of Climate Change) process. These projections are reasonable scenarios for the future, and based on these scenarios, the U.S. and other countries can begin to plan and determine the types of reductions that will be necessary to limit emissions of greenhouse gases. A range of estimates is available for the IPCC report and may be cited in the GAO report.

Further, it should be emphasized that there is strong scientific consensus that there will be an increase in concentrations of greenhouse gases resulting in increased temperatures. While model limitations do not allow us to accurately predict the extent and timing of the temperature increase, evidence of warming above natural variability will probably become apparent early in the next century.

Emissions Reductions

The Agency agrees with the GAO that there are many opportunities for reducing emissions of greenhouse gases at low costs. As indicated in the draft report, these include energy efficiency and increased use of renewable energies. They also include reducing methane from landfills. The GAO report states that this is a relatively small source. However, reducing methane from landfills can have a relatively large impact since only a 10 to 20 percent reduction in methane emissions is required to stabilize atmospheric concentrations. Other areas for reducing emissions include coal mining activities, animal wastes, and livestock. In addition, measures to increase sinks for atmospheric carbon through sequestration or other biological means should be mentioned. The report should observe that these opportunities exist and that in some cases additional research, particularly for renewable energy, would lead to greater implementation of these techniques.

4

While there are disadvantages to different types of renewable energies, these limitations may have solutions or may not exist in all regions of the country. For example, there is abundant land in the southwest United States for solar energy installations, and the geothermal industry has developed methods of extracting geothermal energy to limit geothermal stress. Thus, renewable energies may play a large role in regional strategies to limit emissions of greenhouse gases. Further, on page 57, the draft report states that renewable energy is "perceived" to be environmentally benign. This is not simply a perception. While the use of renewable energy sources does have environmental impacts, they tend to be far less serious, more localized, and often easier to address than those caused by fossil fuel use.

Now on p 52.

International Policy Framework

Finally, the report's discussion in Chapter 4 of a "policy framework to address global climate change" omits any reference of the international consensus on the urgent need for a framework convention on climate change and the United States' active role in that process. Further, the discussion of the timing of responses to global warming (on page 64 of the draft report) also appears to ignore a significant commitment by industrialized nations as stated in paragraph 16 of the Noordwijk Declaration: "Industrialized nations agree that...stabilization [of greenhouse gas emissions, 'while ensuring stable development of the world economy,'] should be achieved by them as soon as possible, at levels to be considered by the IPCC and the Second World Climate Conference of November 1990." Similarly, in paragraph 29, the Declaration "urges all involved or to be involved in the [framework convention] negotiations to do their utmost to conclude these negotiations to ensure adoption of the convention as early as 1991 if possible and no later than at the Conference of the United Nations on Environment and Development in 1992." The Administration has offered to host the first negotiating session for a global climate convention and continues to support an acceleration in analysis of targets and options as identified at the Noordwijk Conference.

Now on p.57.

Thank you for the opportunity to respond to the draft report.

Sincerely,

Thomas E. Kelly for

Terry Davies
Assistant Administrator

Enclosure

NASA's Comments

NASA

National Aeronautics and Space Administration

Washington, D.C. 20546

Office of the Administrator

April 24, 1990

Mr. Richard L. Hembra
Director, Environmental Protection Issues
United States General Accounting Office
Washington, DC 20548

Dear Mr. Hembra:

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the General Accounting Office (GAO) draft report entitled, Global Warming: Emission Reductions Possible While Scientific Uncertainties Being Resolved (GAO/RCED-90-58).

NASA applauds the efforts by the GAO to address the very complex and important issues related to global warming. There is a compelling need to help policy makers understand the complexities and uncertainties surrounding these issues so that governments can make informed decisions and take actions that are soundly based. The report has the potential to help meet this need.

Unfortunately, the depth and timeliness of the report are handicapped in two ways. First, page limitations prescribed for GAO reports lead to a treatment of the issues in the Executive Summary in a manner that risks presenting the diverse and complex problems related to understanding and forecasting global warming in an oversimplified manner. Consequently, a careful reading of the main body of the report will be essential for anyone who wishes to begin to understand, for example, the distinctions between deforestation and fossil fuel burning as sources of carbon dioxide at different times in history, the uncertainties regarding the loss mechanisms for carbon dioxide, the uncertainties regarding the sources of methane and nitrous oxide, and the meaning of the use of an "equivalent" doubling of carbon dioxide by modellers. Even in the main text, report length constraints have apparently forced the GAO authors to neglect important considerations such as the relative roles of additional radiative forcing agents other than greenhouse gases (e.g. aerosols, albedo, solar variability) and the relatively poor state of development of global ocean circulation models compared to global atmospheric circulation models.

2

Second, the report is limited by having to treat a rapidly evolving body of scientific knowledge while being constrained to rely on material already available in the published literature. A major new report by the Intergovernmental Panel on Climate Change (IPCC) is now undergoing review for release later this year. That report is likely to present important new findings and improved assessments of key questions such as the range of temperature increases predicted by high resolution models, estimates of the atmospheric lifetime of carbon dioxide, and the use of coupled ocean-atmosphere models. Consequently, we must remember to encourage interested readers to study also the IPCC report when it becomes available.

Finally, I want to express my appreciation for the opportunity for members of NASA's technical staff and your audit staff to have a number of very positive and constructive discussions during our review of the draft report.

Sincerely,

John E. O'Brien
Assistant Deputy Administrator

NOAA's Comments

UNITED STATES DEPARTMENT OF COMMERCE
The Under Secretary for
Oceans and Atmosphere
Washington, D.C. 20230

APR 3 1990

Mr. Richard L. Hembra
Director, Environmental Protection Issues
Resources, Community, and Economic Development Division
United States General Accounting Office
Washington, D.C. 20548

Dear Mr. Hembra:

Thank you for your letter requesting the Department's comments on the draft General Accounting Office report entitled Global Warming: Emission Reductions Possible While Scientific Uncertainties Being Resolved (GAO/RCED-90-58).

Due to the time constraints, we have only been able to give this draft GAO report a cursory review. We do have some difficulty with the report in that it does not represent a true scientific consensus of global warming phenomena; rather, it is a summary of recent, but not current, findings of individual groups. As such, the report, written by non-scientists, tends to over-simplify a real and very complex scientific issue, thereby potentially distorting policy deliberation. For example, the report cites a much higher temperature range (5-8 degrees F) than the current best estimates (3-8 degrees F) and does not address the recent model findings of hemispheric temperature differences.

The report makes an assumption that the effects will occur and that they will be negative, even though there is, as yet, uncertainty in many areas. The new findings suggest that future changes may not be as severe as indicated. Indeed, the United States is only just embarking on a major research program to attain a better understanding of the entire climate system.

It is also very important to note that an internationally-acknowledged assessment of the science, response strategies, and impacts of global change will be forthcoming this summer from the Intergovernmental Panel on Climate Change. These assessments have been made by experts in relevant fields and will be a more up-to-date evaluation of global change than this GAO report.

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THE ADMINISTRATOR

-2-

We agree with the issue formulation offered by GAO--that policy makers must "weigh the risk of more adverse impacts" against taking "costly actions" that may prove unwarranted. Unfortunately, the report does not follow through by analyzing information on the economic costs of global warming essential in calculating the costs of mitigation or adaptation strategies, though some estimates have been developed by private sector and government analysts. Nor does the report offer any analytic framework for evaluating these issues.

As the need for policy makers to consider economic effects is critical, we recommend that GAO add a chapter to the report surveying estimates of the net economic costs associated with global warming and the economic costs of mitigation and adaptation strategies. At a minimum, we feel that GAO should explicitly indicate that economic information is required before policy makers can judge whether proposed actions are warranted.

The specific view offered by GAO that its work "shows that" actions such as increasing energy efficiency "makes sense for other reasons" is not supported by the discussion or evidence in the draft report. Though noting that "some environmental groups" believe that the price of energy "does not reflect its true social cost", no further evidence is offered to indicate that the true social cost of energy is higher than current prices. We recommend that this conclusion either be deleted or that the supporting work be included in the report.

Additional, specific comments follow:

Page	Comment
3	...half of the expected temperature ("potential temperature" has a precise scientific meaning; its use as a phrase should be avoided in this context).
4	This is inconsistent with the body of the text. What is really said is the ensemble of greenhouse gases are expected to increase such that their net effect is radiatively equivalent to a doubling of CO_2 itself.
13	Greater mention of the central role of CES on the interagency is warranted. Rather than simple coordination, CES has put together an overall program together with joint agency budget submissions. Overall research priorities have been developed with the concurrence of the NAS Committee on Global Change.

Now on p. 16.

-3

Now on p. 17.	14	... Geophysical Fluid Dynamics...
Now on p. 17.	14	"Joint Oceans Institute" should be Joint Oceanographic Institutions, Inc.
Now on p. 18.	15	... objective, we obtained...
Now on p. 23.	21	Despite the DOE reference, the statement that "all of the increase [in atmospheric carbon dioxide] is due to human activities" is a bit strong in light of our present understanding of natural sources and sinks in the global carbon cycle. A major debate is currently underway as to whether a major Northern Hemisphere terrestrial sink exists.
Now on p. 30.	29, footnote	This is not right (see pg.4,Par.2,lns.3-4 comments above). You might try: (lns.2-4, ...that the effect of a suite of trace gases acts to change the infrared radiative forcing by an amount equivalent to that which would be produced by a doubling of CO_2 only. Modelers usually...)
	30	...according to most scientists,...
Deleted	30, footnote	...Sulfur dioxide could cause clouds to...
	31	The model results cited in Table 3.1 are, I believe, equilibrium calculations. Therefore they cannot give information on timing of projected warming. Other model calculations cited in the text are indeed time-dependent; the difference should be spelled out.
Now on p. 31	32	...scientists at GISS...
Now on p. 34.	36	...phenomena...
Now on pp. 40-41.	44	If the discussion of current and future climate-related satellite plans is needed, mention of only ERBE and TRMM is quite a short list. What about EOS? This is by far the largest single item in the U.S. Global Change Research Program.
Now on pp. 44-60.	47-66	It is beyond NOAA's scope to comment directly on policy recommendations. However, a few points of detail are noted below.

-4-

Now on p. 55.

61 This statement is only partially correct. It is only the combustion-related pieces of the methane (natural gas losses) and nitrous oxide that are directly related to carbon dioxide controls. The agricultural, fertilizer, and animal sources probably dominate.

Now on p. 56.

62, footnote The climate and ozone effects anticipated from HCFC's and related compounds are already rather well characterized. Roughly, their greenhouse potential is the same as CFC's on a molecule-per-molecule basis. Their appeal is because they have much shorter lifetimes. This reduces their concentrations for a given source strength and allows less reactive chlorine to be liberated in the active ozone layer.

We appreciate this opportunity to comment on the draft report.

Sincerely,

John A. Knauss

Major Contributors to This Report

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