United States General Accounting Office

GAO

Report to the Ranking Minority Member, Committee on Commerce, House of Representatives

July 1995

GLOBAL WARMING

Limitations of General Circulation Models and Costs of Modeling Efforts

GAO/RCED-95-164

GAO

United States
General Accounting Office
Washington, D.C. 20548

Resources, Community, and
Economic Development Division

B-261119

July 13, 1995

The Honorable John D. Dingell
Ranking Minority Member
Committee on Commerce
House of Representatives

Dear Mr. Dingell:

Increasingly, emissions of heat-trapping greenhouse gases from energy production, industry, transportation, agriculture, and other human activities are being concentrated in the earth's atmosphere. During the Forum on Global Climate Change Modeling, held in October 1994, scientists agreed that the buildup of these gases is creating an enhanced greenhouse effect that will lead to global warming. Specifically, they estimate that the surface temperature of the earth will rise by 1 to 4 degrees Fahrenheit from 1990 to 2050 if emissions continue to grow without restriction. An increase of such magnitude could begin to melt the polar ice caps and, in turn, raise the sea level and alter weather patterns (particularly patterns of precipitation). These changes could bring about the extinction of certain plant and animal species as they shift to adapt to a warmer climate.

Anticipating that costly actions may be needed to avoid or respond to global warming, policymakers are seeking accurate information about possible future climatic changes. The most highly developed tools now available to project climatic changes are complex computer models called general circulation models (GCM). These models, whose development is supported through a coordinated effort of the U.S. Global Change Research Program and five federal agencies, have become more accurate during the last few decades, but important uncertainties still limit their predictive capabilities. Given the pivotal role that GCMs could play in shaping the response of U.S. policymakers to possible future climatic changes, you asked us to identify the (1) factors limiting the accuracy of GCMs' estimates of future climatic changes and (2) federal expenditures for GCMs from fiscal years 1992 through 1994.

Results in Brief

General circulation models are considerably better now than they were a decade ago at predicting future climatic changes. Nevertheless, the accuracy of their estimates is still limited, primarily by their incomplete or inaccurate representation of the processes affecting climate and by insufficient computer power. For general circulation models, as for other computer models, the quality of the output depends upon the quality of the input—the models are only as good as the data and the scientists' understanding of how the climate system works. When scientists do not fully understand how the climate system responds to potentially important physical, chemical, and biological processes, they can omit or poorly represent the operation of these processes in the models. Such omissions or poor representations produce inaccuracies in the models' projections of future climatic conditions. Limitations on computer power have led to the use of (1) simplifying assumptions that increase the uncertainty of the models' predictions and (2) simplifying structures that preclude the incorporation of the detailed data needed to accurately project regional and local conditions. Efforts to overcome these limitations and improve the accuracy of the models' estimates are ongoing.

For fiscal years 1992 through 1994, federal agencies reported spending an estimated $122.6 million to fund various projects for modeling global climate change; these expenditures represented approximately 3 percent of the U.S. Global Change Research Program's multiagency budget over this period.[1] Five U.S. agencies operate and/or fund such projects: the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), and the Environmental Protection Agency (EPA). DOE and NASA operated the largest modeling programs and reported spending approximately 64 percent of the total federal funds. The modeling projects were conducted under contracts and grants with various research laboratories and universities throughout the United States.

Background

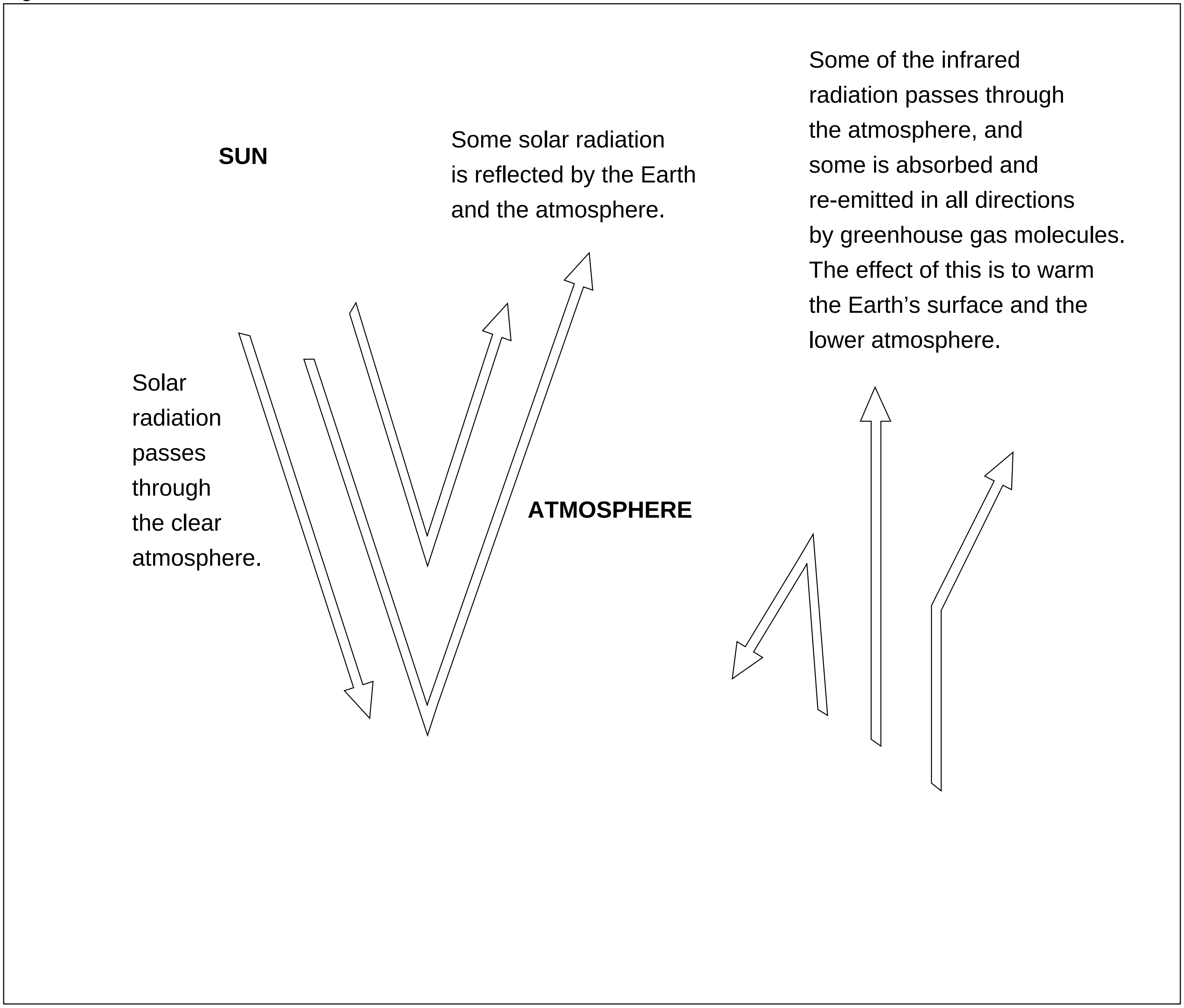
The sun provides the energy that determines the climate and weather. Solar radiation passes through space and is largely absorbed by components of the global climate system (the atmosphere, oceans, and land, as well as the biosphere, which includes all living things); the remaining radiation is reflected. The solar radiation absorbed by the earth's surface is released as infrared radiation. Some of this radiation passes back through the atmosphere, and some is absorbed in the atmosphere by the molecules of gas—principally water vapor, carbon dioxide, methane, and chlorofluorocarbons—known collectively as greenhouse gases. These gas molecules act as a partial thermal blanket,

[1]Established in 1990, this program combines and coordinates the global change research and policy development interests of all U.S. departments and agencies.

trapping much of the heat energy and redirecting it to the earth's surface and lower atmosphere. This naturally occurring process, called the greenhouse effect (see fig. 1), helps to maintain the earth's temperature at an average of approximately 60 degrees Fahrenheit.[2]

[2]All temperatures are reported in degrees Fahrenheit.

Figure 1: The Greenhouse Effect



Source: U.S. Department of State, 1992.

Additional atmospheric warming—called the enhanced greenhouse effect or global warming—appears to be associated with human activities. During the past century, as industry, agriculture, and transportation have grown, so, too, have atmospheric concentrations of heat-trapping greenhouse gases (see app. I). At the same time, the earth has gotten warmer, according to historical data. Recorded temperatures for the period from 1860 through 1993 show a warming trend that generally coincides with the increased use of fossil fuels during the Industrial Revolution—and, hence, with the increased emission of greenhouse gases.

During the past 50 to 100 years, volcanic eruptions have combined with the increased combustion of fossil fuels and emission of greenhouse gases to increase the concentration of aerosols[3] in the lower atmosphere. Scientists believe that because these aerosols deflect sunlight, they have partially offset the effects of global warming. As a result, scientists surmise, temperatures have not reached the levels projected by GCMs, which do not include the aerosols' effects.

To help understand the global climate system's response to emissions of greenhouse gases, scientists use three types of GCMs: atmospheric, oceanic, and coupled. In general, atmospheric GCMs predict the physical behavior of the atmosphere. Oceanic GCMs represent the physics of the ocean. Coupled GCMs, which scientists regard as the most advanced of the models, physically join atmospheric and oceanic GCMs and treat the evolution of the climate in both domains. To improve predictions of the future climate, modelers are also striving to couple, and to some degree have coupled, (1) the land surface to the atmosphere and (2) the Antarctic sea ice to both the ocean and the atmosphere.

All types of GCMs process vast quantities of data on variables affecting climate. Using complex mathematical equations to represent the actions and interactions of these variables, the GCMs process the data to project patterns of climatic conditions. (App. II shows how a coupled GCM works.) To test the accuracy of a model's projections, modelers run the model with their best estimates of historical climatic data and compare the resulting projections with records of actual climatic conditions for the period being modeled. Modelers assume that if the model can accurately simulate actual climatic conditions for prior periods, then it can be used to accurately project future climatic conditions.

[3]Aerosols are gases that bear other substances.

Although the earth's gradual warming since the mid-19th century is generally consistent with GCMs' estimates of the effects of greenhouse gases (when adjusted for the effects of aerosols), scientists have not been able to attribute the warming conclusively to the enhanced greenhouse effect or to quantify its effects. Specifically, they have not been able to uniquely and quantitatively distinguish the effects of higher concentrations of greenhouse gases from the effects of other factors that can change the climate. Such factors include natural fluctuations in the global climate system, increases in atmospheric ozone, air pollution, and aerosols emitted into the atmosphere from volcanic eruptions. Until more is known about the relative influence of these various factors on the earth's climate, GCMs' estimates of global warming will remain uncertain.

Factors Limiting the Accuracy of Models' Estimates

Over the last decade, GCMs have accurately simulated many elements of the observed climate, providing useful indications of some future climatic conditions. For example, atmospheric models have demonstrated some skill in portraying aspects of atmospheric variability, such as the surface temperature of the sea. Oceanic models have also simulated the general circulation of the ocean, including the patterns of the principal currents. Coupled models, though still prone to small-scale errors, have simulated the current climate on a large scale as well as portrayed large-scale atmospheric and oceanic structures.

This progress notwithstanding, the models remain limited in their ability to estimate, with desired accuracy, the magnitude, timing, and regional distribution of future climatic changes. These limitations stem from scientists' imperfect understanding of the global climate system and computers' insufficient capacity to perform more detailed simulations. More specifically, the accuracy of the models' predictions is limited by (1) incomplete or inadequate representations of the processes affecting climate and (2) insufficient computer power. Research is being conducted to overcome both the scientific and the technical limitations affecting the accuracy of GCMs' estimates.

Incomplete or Inadequate Representation of Processes Affecting Climate

According to the U.S. Global Change Research Program, most GCMs include the most important processes that affect climate, such as radiation, convection, and land surface exchanges. However, some models do not include or fully incorporate some processes, and even the most advanced models do not adequately represent the interactions of some processes. None of the models fully incorporates certain components of the global climate system, called feedbacks or feedback mechanisms, and none adequately represents the interactions of these mechanisms with greenhouse gases, called feedback processes.

Some Processes Not Included or Fully Incorporated in Some Models

Atmospheric and oceanic GCMs include fewer processes than coupled GCMs, and their simulations are, therefore, more limited and, in some cases, less accurate. Atmospheric models do not fully portray the influence of oceanic pressures (currents) and fluctuations in climate, while oceanic models do not fully account for the effects of atmospheric surface winds. The omission or incomplete incorporation of some processes may introduce errors into these models' projections. For example, atmospheric models tested in 1991 produced systematic errors in their projections of sea level pressure, temperature, zonal wind, and precipitation. Compared with atmospheric and oceanic GCMs, coupled GCMs include more processes and interactions at the ocean-atmosphere interface, but even they do not include critical biospheric and chemical interactions with the atmosphere. The U.S. Global Change Research Program is supporting efforts by modeling groups to include more complete sets of processes in their models and to identify systematic errors in the models.

Inadequate Representations of Interactions Among Variables

Although coupled GCMs produce more comprehensive simulations of current climatic conditions than either atmospheric or oceanic GCMs, their simulations still differ from actual conditions. Modelers believe that these models are impaired by a condition known as climatic drift, which results from imbalances in the models' analyses of heat and moisture variables. These imbalances cause the models' estimates of temperature and precipitation to deviate from actual conditions. For example, in an experiment conducted by the National Center for Atmospheric Research in 1988, the models estimated wintertime ocean temperatures that were 7 degrees warmer than observed temperatures for the icebound region of Antarctica and 9 degrees colder than observed temperatures for the tropics.

Modelers either accept climatic drift or try to correct its effects by inserting adjustments, called flux adjustments. Because flux adjustments artificially improve the models' performance, their use is controversial. Scientists believe that an increased understanding of the interactions between atmospheric and oceanic variables—and, hence, a more accurate mathematical representation of these interactions—may eventually remove the need for flux adjustments. Reducing the need for flux adjustments is an objective of coupled model research.

Inadequate Representation Of, or Accounting For, Feedback Mechanisms

GCMs include many of the most important feedback mechanisms, such as vegetation, water vapor, ice cover, clouds, and the ocean. However, the models do not yet adequately represent the interactions of these mechanisms with greenhouse gases. Such interactions can amplify, dampen, or stabilize the warming produced by increased concentrations of greenhouse gases.

The influence of feedback mechanisms on climate is likely to increase as concentrations of greenhouse gases increase; however, modelers do not fully understand the effects of these mechanisms and have not learned how to represent them with sufficient accuracy in models. Although they have clarified the role of water vapor and improved their ability to model its effects, they are still seeking to understand and accurately model the effects of clouds, which have the greatest potential of all the feedback mechanisms to amplify or moderate global warming. Recent studies have shown that different schemes for modeling cloud formation processes can lead to substantially different projections of the earth's temperature. In 1989, for instance, two simulations, which varied only in their treatment of the cloud feedback process, produced estimates of the increase in the earth's annual average surface temperature of 4.9 and 9.4 degrees, respectively.

Insufficient Computer Power

Insufficient computer power affects the accuracy of GCMs' estimates because even the most powerful computers are limited in their ability to store and analyze the vast quantity of data required to accurately simulate changes in the global climate. Modelers have tried to overcome these limitations by introducing assumptions into their models that deliberately oversimplify some operations in order to free the GCMs' capacity and time for other, more critical operations. For example, modelers have assumed that the ocean was not warmed by emissions of greenhouse gases before 1985. Although this assumption gains capacity for the GCMs, it introduces an error, called the cold start error, that increases the uncertainty of the GCMs' predictions. Another oversimplification, the division of the earth into relatively large grids for analytical purposes, prevents the GCMs from accurately predicting regional changes in climate.

Cold Start Error

Simulations by coupled GCMs that are calculated on the assumption that the ocean was not warmed by increased emissions of greenhouse gases before 1985 do not adequately account for the ocean's reduced capacity to absorb these emissions. In fact, the ocean will reach its capacity for absorbing these emissions sooner—possibly decades sooner—than the coupled GCMs calculate. It will then deflect more of the heat-trapping emissions to the atmosphere, thereby enhancing global warming more rapidly than the models predict.

While recognizing that the cold start error artificially delays the onset of global warming in GCMs' predictions, scientists do not know by how much or by how long it distorts the predictions. Overall, they believe that it causes the models to underestimate the change in temperature that will result from the emissions. Modelers have shown that the cold start error can cause projections of the earth's average annual temperature to differ by as much as 0.7 degrees after 50 years.

According to scientists, an extraordinary commitment of computer time would be required to project the timing of future temperature changes more accurately. Completing the number of computer runs needed to arrive at more precise timing projections could take many months even on a state-of-the-art supercomputer.

Inability to Project Regional Changes in Climate

Still another limitation affecting the accuracy of GCMs' estimates is the relatively large size of the grids into which the models divide the earth. These grids typically cover an area about the size of South Carolina. Although their use enables GCMs to depict larger-scale regional effects in relatively large, homogeneous regions, it does not allow modelers to incorporate detailed regional features. Consequently, the use of large grids prevents the models from accurately forecasting climatic changes for smaller, less homogeneous regions. The use of smaller grids would permit the incorporation of more detailed features that could be used to project regional changes more precisely. However, models using smaller grids would take longer to run.

Each grid contains a single value for each variable for the entire area represented. Today's grids are smaller than those we described in our 1990 report on global warming,[4] but they are not yet small enough to produce the information policymakers and planners need to develop strategies for adapting to regional changes.

Researchers believe that the combination of greater computer power, which would permit the use of smaller grids, and greater understanding of cloud formation processes, which would permit the incorporation of this

[4]Global Warming: Emission Reductions Possible as Scientific Uncertainties Are Resolved (GAO/RCED-90-58, Sept. 28, 1990).

important but often excluded feedback mechanism, would produce more accurate projections of regional climatic changes.

Improving GCMs' Estimates

To improve the accuracy of GCMs' estimates, scientists are developing models that incorporate more of the processes affecting the climate system (particularly cloud formation processes) and better reflect interactions among various components of the climate system, including interactions between or among the ocean and the atmosphere; the land surface, the biosphere, and the atmosphere; and the cryosphere (frozen regions), the ocean, and the atmosphere. They are also developing larger and faster computers that can manipulate data for longer periods of time and smaller grids. In addition, they are collecting more data and conducting more research on the processes affecting climate and improving the international exchange of such data. Various international programs, such as the World Climate Research Programme[5] and the Global Climate Observing System,[6] currently have efforts under way to address these actions.

In commenting on a draft of this report, the Director of the Office of the U.S. Global Change Research Program and agency officials stated that the program has several ongoing efforts to address the limitations of GCMs discussed in this report. For example to address the models' inadequate representation of processes affecting the climate, the program is devoting approximately 30 percent of its $1.8 billion budget for fiscal year 1995 to conduct research aimed at improving scientific understanding of these processes. In addition, to address the need for increased computer power, the program has, through NSF, established a dedicated computing facility for modeling the climate system, known as the Climate Simulation Laboratory, in cooperation with the National Center for Atmospheric Research. This facility will provide state-of-the-art computer resources and data storage systems for use in major modeling research simulations. The goals and funding for the U.S. Global Change Research Program's fiscal year 1995 research programs are summarized in appendix III. Further information on the program's efforts to reduce the uncertainties of GCMs' projections appears in a letter from the Subcommittee on Global Change Research, which is reproduced in appendix VI.

[5]This program was established as a joint undertaking of the International Council of Scientific Unions and the World Meteorological Organization, a United Nations agency, to foster an improved understanding of the climate's variability and prediction.

[6]This international organization was established in 1992 to monitor climatic changes and obtain data for application to national economic development.

Federal Expenditures for GCMs

Five federal agencies reported spending an estimated $122.6 million during fiscal years 1992 through 1994 to fund modeling activities to improve predictions of the future climate.[7] As shown in table 2, the agencies reported spending approximately $36.9 million, $40.5 million, and $45.3 million for these projects in fiscal years 1992, 1993, and 1994, respectively. Of the five agencies, DOE had the largest climate change modeling program, representing about 36 percent of the total cost for all 3 years.

Table 1: Estimated Costs of Modeling Global Climate Change, Fiscal Years 1992-94

Dollars in millions

Agency	1992	1993	1994	Total	Percent
DOE	$14.1	$15.2	$15.2	$44.5	36%
NASA	10.5	11.8	12.6	34.9	28%
NSF	7.4	7.5	9.2	24.1	20%
NOAA	4.1	4.1	6.0	14.3	12%
EPA	.7	1.8	2.3	4.8	4%
Total[a]	$36.9	$40.5	$45.3	$122.6	100%

Note: The above costs are approximate because computer resources were funded separately in some agencies and because some projects had multiple components. The costs include expenditures for projects whose primary focus is modeling the global atmosphere, oceans, and/or land surface for the purpose of simulating changes in the global climate. Projects include (1) predicting changes in the climate that are likely to occur from the next decade through the next century and (2) simulating the current climate.

[a]Totals may not add because of rounding.

Appendix IV presents background and cost information on each agency's climate modeling program. Most of the agencies' climate modeling research was contracted out to universities and research laboratories throughout the United States. These modeling activities were conducted at five major modeling centers in the United States: 1) the National Center for Atmospheric Research in Boulder, Colorado; 2) NOAA's Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey; 3) NASA's Goddard Institute for Space Studies in New York, New York; 4) NASA's Goddard Space Flight Center in Greenbelt, Maryland; and 5) DOE's Lawrence Livermore National Laboratory in Livermore, California.

Conclusions

Although the accuracy of general circulation models' estimates of climatic change has improved over the past decade, these estimates are still limited

[7]During fiscal year 1994, the U.S. Global Change Research Program was funded at $1.4 billion. Modeling activities accounted for $45.3 million, or 3 percent of the funding.

by incomplete and inaccurate representations of the processes affecting climate and by insufficient computer power. These limitations prevent scientists from carrying out analyses that would yield more precise information about the magnitude, timing, and regional effects of predicted increases in warming. Ongoing efforts to collect and analyze data, improve representations of climatic processes, and, develop and apply more powerful computers should improve the accuracy of the models' estimates. Whether these estimates will provide policymakers with the information they need to respond to possible future climatic changes will depend on the degree of certainty expected from the models, the resources provided to improve the models, and advances in scientists' fundamental understanding of the climate system.

Agency Comments

We obtained comments from representatives of DOE, NASA, NSF, NOAA, and EPA. According to these comments, which were coordinated by the Director of the Office of the U.S. Global Change Research Program, the agencies found, overall, that this report provided an interesting and useful perspective on the most important factors that limit the credibility of general circulation models' projections of future climatic conditions. However, the agencies believed that the report would be more useful if it provided some perspective on what the modeling community has learned about the models' limitations and what efforts are under way to address them. The agencies also believed that the report focused too heavily on the limitations of the models while remaining largely silent on their accomplishments. We have responded to the agencies' comments by adding information about ongoing research to overcome the models' scientific and technical limitations and about recent positive results achieved with the models.

Additionally, the agencies believed that the report should include, in full, the report of the Forum on Global Climate Change Modeling (Forum), which was developed to inform policymakers about the issues associated with using general circulation models. While we believe that the Forum's document is useful, we did not include it in this report because its major points are summarized in the agencies' detailed comments and are included in the body of this report, insofar as they pertain to the objectives of this assignment. Furthermore, since the Forum's report is available to the public from the Office of the U.S. Global Change Research Program (USGCRP Report 95-01, May 1995), we believe that persons desiring the additional detail may request the document. The agencies' comments and our response appear in appendix VI.

We conducted our work between September 1994 and June 1995 in accordance with generally accepted government auditing standards. We reviewed various scientific documents that discussed the models' limitations and the implications of these limitations. Through the Director of the Office of the U.S. Global Change Research Program, we collected data on costs from the five agencies that fund U.S. global climate change modeling. We did not independently verify the validity of the cost data. Appendix V more fully discusses our scope and methodology.

As arranged with your office, unless you publicly announce its contents earlier, we plan no further distribution of this report until 30 days after the date of this letter. At that time, we will send copies to the Director of the U.S. Global Change Research Program and other interested parties. We will make copies available to others upon request.

Please call me at (202) 512-6111 if you or your staff have any questions. Major contributors to this report are listed in appendix VII.

Sincerely yours,

Peter F. Guerrero
Director, Environmental
Protection Issues

Contents

Abbreviations

DOE	Department of Energy
EPA	Environmental Protection Agency
GAO	General Accounting Office
GCM	general circulation model
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
USGCRP	U.S. Global Change Research Program

Growth in the Production of Greenhouse Gases and Their Contribution to the Enhanced Greenhouse Effect

Over the past century, human activities have significantly increased atmospheric concentrations of carbon dioxide, methane, and nitrous oxide—known, together with water vapor, as greenhouse gases.[8]

Emissions of carbon dioxide, the most abundant greenhouse gas after water vapor, increased by about 25 percent from preindustrial times until 1993. Currently, the growth in emissions is primarily attributable to the increased use of fossil fuels, whereas, in the 19th and early 20th century, it was due to deforestation and the expansion of agriculture. Methane emissions increased by about 9 percent between 1978 and 1987 and have more than doubled since preindustrial times. Nitrous oxide emissions increased by about 9 percent from preindustrial times until 1993. Table I.1. details the increases in greenhouse gas emissions, the periods when the increases occurred, and the sources of the emissions.

Table I.1: Growth in the Production of Greenhouse Gases

Gas	Growth (percent)	Applicable period	Sources
Carbon dioxide	25	Preindustrial to 1993	Fossil fuel combustion Deforestation
Methane	9	1978 to 1987	Rice paddies Cattle and sheep Natural gas production and delivery Coal production Landfills
Nitrous oxide	9	Preindustrial to 1993	Nylon production Nitric acid production Use of nitrogenous fertilizers

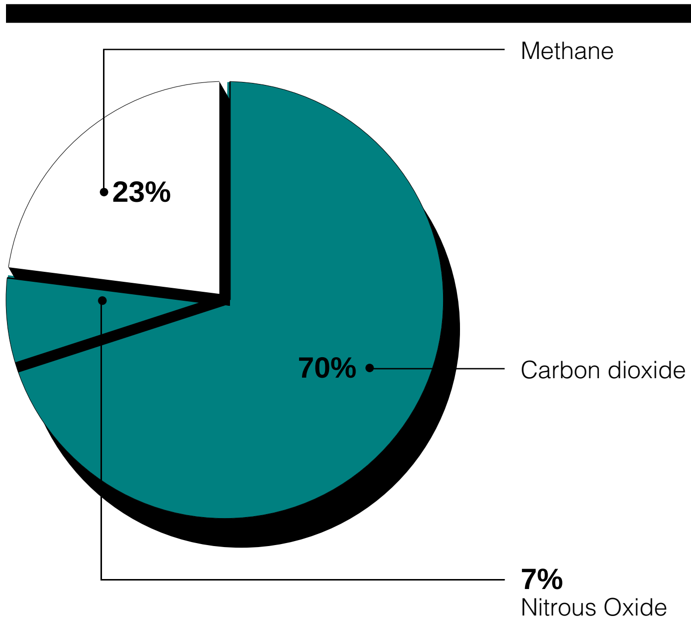
Source: Preparing for an Uncertain Climate, Vol. I, Office of Technology Assessment (Oct. 1993).

The relative contribution of each gas to the enhanced greenhouse effect is determined by the ability of the gas to absorb infrared radiation and by its atmospheric abundance. Atmospheric abundance is determined by the quantity of gas emitted and by its atmospheric life span. For example, although a methane molecule is a more effective absorber of infrared radiation than a carbon dioxide molecule, it contributes only about a third as much to the enhanced greenhouse effect because it is less abundant.

[8] Although chlorofluorocarbons may also be referred to as major greenhouse gases, we did not include them in our categorization of major gases because their consumption has declined since their phaseout under the 1987 Montreal Protocol.

Carbon dioxide is believed to have contributed 70 percent of the enhanced greenhouse effect from the beginning of the Industrial Revolution up to 1990. Figure I.1 depicts the relative contributions to the enhanced greenhouse effect from the cumulative contributions of carbon dioxide, methane, and nitrous oxides. Chlorofluorocarbons are not included in the figure because, unlike carbon dioxide, methane, and nitrous oxide, their atmospheric concentrations vary considerably across the globe and are difficult to quantity.

Figure I.1: Contributions of Greenhouse Gases to the Enhanced Greenhouse Effect

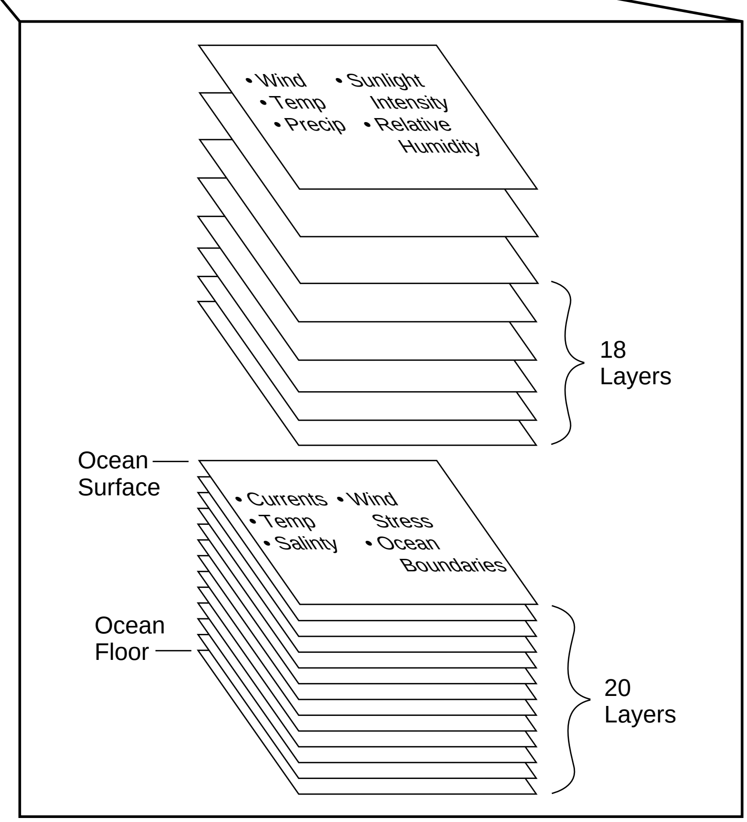


Source: John Houghton, Global Warming (Lion Publishing: Elgin, Ill., 1994).

How General Circulation Models Work

General circulation models (GCM) are the most advanced tool that scientists have to model climate and predict climatic change. These models comprise complex mathematical equations that describe various physical processes and interrelationships, including seasonal changes in sunlight, global air currents, and other factors that affect the climate. Because the equations are so complex, modelers cannot solve them exactly and consequently must segment the earth into a discrete number of grids to approximate the solutions. The coupled model depicted in figure II.1 calculates solutions for 18 layers above each grid (extending from the ocean's surface to the top of the atmosphere) and 20 layers below each grid (extending from the surface to the floor of the ocean).

Figure II.1: How One General Circulation Model Works



- Earth is divided into a gridwork of 50, 520 “boxes”.
- The atmosphere above each box is divided into 18 layers.
- The ocean under each box is divided into 20 layers.
- Each layer’s program represents a set of variables (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.

U.S. Research on Global Climate Change and Its Estimated Costs

The U.S. Global Change Research Program (USGCRP) provides insight into the causes and effects of changes in the earth's climate system, especially those related to human activities, and is developing tools to assess options for responding to global change. As the depth of understanding grows, the research results are intended to provide increasingly valuable support for formulating national and international policy, as well as for evaluating the impact and effectiveness of the actions taken. The research activities are grouped by major focus in six broad categories:

- observing the earth's climate system through land, ocean, and satellite observation networks;
- managing data and information to ensure that they are preserved and available for national and international researchers to use;
- understanding global change processes, ranging from cloud formation and hydrologic processes to the accumulation of atmospheric ozone;
- predicting the magnitude, timing, and extent of global change;
- evaluating the consequences of global change by analyzing the impact of global change on the environment and on society; and
- assessing policies and options for responding to global change.

The President's fiscal year 1995 budget for the research activities is summarized in table III.1.

Table III.1: President's Fiscal Year 1995 Budget for the U.S. Global Change Research Program, by Category of Research

Dollars in millions

Category	Fiscal year 1995 budget
Observing the earth's climate system	$733.7
Managing data and information	382.0
Understanding processes	530.7
Predicting change (modeling)	67.1
Evaluating consequences	67.1
Assessing policies and options	34.7
Total	**$1,814.8**

Note: Total may not add because of rounding.

Source: Our Changing Planet: The FY 1995 U.S. Global Change Research Program.

Modeling Global Climate Change in the United States—Activities and Costs

The earth's environmental system encompasses the atmosphere; the oceans and marine life; the land surface and biosphere (plant and animal life); and the cryosphere (snow, glaciers, sea ice, and icecaps). Because this complex, interconnected system cannot be reconstructed and experimented with in the traditional laboratory sense, numerical models are used to simulate the behavior of the earth's system and its fluctuations, variations, and responses to disturbances, including the effects of human activities. Coupled atmospheric/oceanic GCMs are, within the limits of available resources and ingenuity, designed to include as much of the important and relevant physics, chemistry, and biology as is understood and as is needed to address particular questions posed to the models about future climatic change.

Areas of Emphasis in Modeling Climatic Change

A wide array of modeling activities supports the need to provide society with the best possible predictions of weather; anomalous seasonal events, such as floods and droughts; fluctuations in the frequency of climatic extremes; and long-term changes in climate. These activities, which are conducted at research centers, universities, and government laboratories, are supported by government agencies that have responsibility for scientific research, including (1) the Department of Energy (DOE), (2) the National Aeronautics and Space Administration (NASA), (3) the National Science Foundation (NSF), (4) the National Oceanic and Atmospheric Administration (NOAA), and (5) the Environmental Protection Agency (EPA). These agencies support research using full models of the global climate to improve, test, and, in some cases, project the future climate and its potential changes. The agencies' roles in modeling climatic change are discussed below.

Department of Energy

DOE's modeling program focuses on changes and variations in the earth's climate—especially those caused by human activities—that may occur over periods ranging from decades to centuries. DOE's program (1) tests the performance of models from around the world by comparing their ability to represent the recent climate, (2) simulates the effects of carbon dioxide emissions on the climate, and (3) develops global models by taking advantage of the new generations of highly parallel computers. These activities are intended to develop the coupled models of the earth's oceans, atmosphere, and land surface that are needed to project the climate more accurately from tens to hundreds of years. During fiscal year 1994, DOE funded modeling research at 24 universities and research centers.

National Aeronautics and Space Administration

NASA's modeling program focuses on developing and applying a four-dimensional model that places special emphasis on the role of data from satellites in providing research-quality information on the climate system. NASA's program supports efforts to (1) better understand the relative roles of the various factors that have changed or are changing the earth's climate; (2) analyze the global effects of feedback mechanisms, such as clouds, that can amplify or moderate climatic change; and (3) develop tools for integrating data from satellites and other sensors into a coherent record of atmospheric behavior. During fiscal year 1994, NASA supported modeling research on climatic change at its Goddard Institute for Space Studies and Goddard Space Flight Center and at two universities.

National Science Foundation

NSF's modeling program focuses on climatic change that occurs over seasons to centuries and provides computer resources to the research community. Specifically, NSF's programs emphasize research on coupling models of the atmosphere, oceans, land surface, and cryosphere into a single integrated model that can simulate the global climate system over the long term. NSF also supports wide-ranging research activities, including simulations of climates of the distant past, of natural variations in the present climate, and of the interactions of the various processes and influences. During fiscal year 1994, NSF funded major modeling research projects at 10 universities and research centers.

National Oceanic and Atmospheric Administration

NOAA's modeling program focuses primarily on seasonal to interannual (year to year) predictions and on better understanding long-term climatic variation and change. NOAA's activities include (1) developing and improving models of the atmospheric-oceanic system, (2) comparing models' simulations to observations and analyses of the processes that most influence climate, (3) simulating the potential climatic effects of increased concentrations of greenhouse gases, and (4) separating the effects of natural climatic variations from the effects of human activities on climate. In addition, NOAA has tried to develop models capable of predicting the seasonal to interannual fluctuations that cause extreme rainfall and other similar disruptions to regional climates. During fiscal year 1994, NOAA supported global general circulation modeling research on 10-year and longer time scales at its Geophysical Fluid Dynamics Laboratory and four universities and research centers.

Environmental Protection Agency

EPA focuses its modeling research on chemical and environmental interactions within the biosphere. It supports research to improve GCMS' representations of ecosystems and of the relationship between chemicals and plant and animal life in an area so that the effects of climatic change on the biosphere and of biospheric change on climate can be projected. During fiscal year 1994, EPA funded modeling research at three universities and research centers.

Costs of Modeling Global Climate Change

As previously stated, five agencies support research on modeling global climate change. This research—through which models of the global climate are improved, tested, and, in some cases, used to project the future climate and the ways it may change—can be grouped into two broad areas:

- modeling to predict changes in climate that may occur over decades and centuries, and
- modeling to simulate the current climate.

The cumulative estimated costs of the five agencies' modeling activities was approximately $123 million during fiscal years 1992 through 1994, as table IV.1 shows.

Table IV.1: Costs of Modeling Global Climate Change, Fiscal Years 1992-94

Dollars in millions

	Modeling category						
	Predicting climatic change over decades to centuries			Simulating the current climate			Total
Agency	1992	1993	1994	1992	1993	1994	1992-94
DOE	$14.1	$15.1	$15.1	$0.0	$0.1	$0.1	$44.5
NASA	1.8	1.6	1.7	8.6	10.2	10.9	34.9
NSF	7.2	7.3	8.8	0.2	0.3	0.4	24.1
NOAA	4.1	4.1	6.0	0.0	0.0	0.0	14.3
EPA	0.7	1.8	2.3	0.0	0.0	0.0	4.8
Total[a]	**$28.1**	**$29.9**	**$34.0**	**$8.8**	**$10.6**	**$11.4**	**$122.6**

[a]Totals may not add because of rounding.

Objectives, Scope, and Methodology

The Ranking Minority Member of the House Committee on Commerce asked us to review the factors that affect the accuracy of GCMs' estimates of future climatic changes and determine the costs of federally funded GCMs for fiscal years 1992 through 1994. We conducted our work between September 1994 and April 1995 in accordance with generally accepted government auditing standards.

To determine the factors that affect the accuracy of GCMs' estimates of future climatic changes, we reviewed information that we previously reported in Global Warming: Emission Reductions Possible as Scientific Uncertainties Are Resolved (GAO/RCED-90-58, Sept. 28, 1990). We also met with headquarters officials at DOE, NASA, NSF, NOAA, and EPA and with the Director of the Office of U.S. Global Change Research Program (USGCRP) to discuss these factors. From these meetings, we obtained various scientific assessments of GCMs' strengths and limitations. In October 1994, the Subcommittee on Global Change Research held the Forum on Global Change Modeling with modelers from throughout the United States. The intent of the forum was to address requests from the White House Office of Science and Technology Policy and the General Accounting Office to produce a consensus document on issues concerning the use of climate models to inform policy on future climatic changes. This forum, whose participants included agency officials, scientists, and academicians involved in studying the global climate, provided information on the strengths and weaknesses of GCMs, as well as other relevant topics. In addition, we searched four scientific data bases to identify additional assessments of the models' limitations. Throughout our review, we met with the Director of the Office of USGCRP to clarify technical issues associated with the models' limitations.

To identify federal funding for GCMs during fiscal years 1992 through 1994, we obtained cost data by agency from USGCRP. We worked with the Director of the Office of USGCRP to develop an instrument to capture all relevant cost components. We did not independently verify the validity of the cost data.

On May 12, 1995, we met with the Director of the Office of USGCRP, the Manager of the Climate Modeling Program at NASA, the Deputy Director of the Office of Global Programs at NOAA, and the Manager of the Global Change Research Program at EPA to obtain their comments on a draft of this report. On May 22, 1995, the Chair of the Subcommittee on Global Change Research provided us with written comments on the draft. These comments integrated the responses of the five agencies included in our review (see app. VI). We have addressed the comments in the text of this report, where appropriate.

Comments From the Subcommittee on Global Change Research

Note: GAO comments supplementing those in the report text appear at the end of this appendix.

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May 22, 1995

nsf

OFFICE OF THE
ASSISTANT DIRECTOR
FOR GEOSCIENCES

Mr. Peter Guerrero
Director, Environmental Protection Issues
Resources, Community, and Economic Development Division
U. S. General Accounting Office
Washington, D.C. 20548

Dear Mr. Guerrero:

On behalf of the Subcommittee on Global Change Research (SGCR), I would like to thank you and the General Accounting Office for providing the opportunity for the five agencies supporting research on global climate system modeling to review the draft version of the new GAO report entitled "GLOBAL WARMING: Limitations of General Circulation Models and Costs of Modeling Efforts." The SGCR is an interagency committee that has responsibility for oversight of the U. S. Global Change Research Program (USGCRP), for which most of the global modeling activities are undertaken. We welcome the interest of Congress and the GAO in reviewing the scientific limitations of the models and the progress being make on research to improve them.

Pursuant to your request, copies of the draft report were submitted for comment to representatives of the Department of Energy, the National Aeronautics and Space Administration, the National Science Foundation, the National Atmospheric and Oceanic Administration, the Environmental Protection Agency, and the White House Office of Science and Technology Policy. Review of the report was coordinated by Dr. Michael MacCracken, director of the Office of the USGCRP, to whom the letter was sent; that office supports the interagency SGCR.

See comment 1.

In reviewing the draft version of the report provided to us on May 3, the five agencies have prepared a single, integrated response to reflect their comments, which were all similar. Briefly, with respect to the overall content of the report, the agencies believe that it is important for the GAO to provide additional perspective on the successes and accomplishments achieved with models in order to provide context for the description of model limitations that is enumerated in the GAO report. The state of modeling has advanced significantly in the past five years, and while models are not yet fully adequate to accurately address all of the questions being asked, they are quite successful in a number of ways. We believe that readers of the GAO report would benefit from having both limitations and successes described, as is done in international and national assessments. This could be readily accomplished by GAO by drawing from and then including in full our general comments and the report of the USGCRP Model Forum that was convened last October and which the GAO representatives attended. We include this Model Forum report as an integral part of our set of general comments.

Mr. Peter Guerrero   Page 2

See comment 2.

As a second general point, we think it would be helpful for the GAO report to indicate that the agencies have a coordinated program, with each agency contributing to the overall effort. This is apparent in the complementary descriptions of the agency programs and areas of emphasis in the appendices, but is not clearly articulated in the body of the report.

As is most effective in scientific research, there are indeed multiple groups pursuing similar problems, but normally in somewhat different ways so as to check each other's findings. Overall, we believe the area is underfunded as compared to international efforts, and for FY-1995 and 1996 have sought additional funding for these activities.

We appreciated the opportunity to discuss these comments with GAO representatives at the meeting on May 12. This letter represents the official submission of comments by the five modeling agencies included in the report.

Sincerely,

Robert W. Corell

Robert W. Corell
Assistant Director for Geosciences
and Chair, Subcommittee on
Global Change Research

Enclosures

See comment 1.

Combined DOC/NOAA, DOE, EPA, NASA and NSF Comments on the April 1995 Draft GAO Report on Factors Limiting the Credibility of GCMs

Submitted May 22, 1995

Summary

The federal agencies involved in modeling the global climate system, and more broadly the government agencies participating in the U. S. Global Change Research Program, welcome the interest of Congress and the General Accounting Office in improving understanding of the research efforts underway to provide a continually improving knowledge base of the effects of natural factors and human influences on climate, the environment, and society. The GAO report has the potential of contributing to the effort of communicating the many challenges faced in making models that realistically represent the climate system. For this report to fully meet this potential, it is the joint position of DOC/NOAA, DOE, EPA, NASA, and NSF that it would be helpful to provide some perspective on what we have learned and can do as context for appreciating the limitations that still exist. We also think it important to point out the efforts that are underway to address the limitations that are indicated and to improve the overall performance of the model simulations.

Background on Modeling

The people of this nation and the world face an important challenge as their numbers grow and their demand on and use of resources increase in ensuring that they do not impose an unsustainable debt on future generations that is reflected in unprecedented environmental change that overstresses ecological and economic systems. Under the leadership of President Bush in 1989 and Congress in 1990, the U. S. Global Change Research Program was established with the goal of providing an improved *predictive* understanding of the Earth system. To achieve this capability, the USGCRP supports substantial efforts to document past changes, to observe present conditions, to assemble information on emissions and alterations form human activities, and to understand how nature's many processes control the behavior of the atmosphere, oceans, terrestrial and marine ecosystems, and the polar snow and ice. These activities are carried out in cooperation with nations around the world and provide the information base needed to underpin the efforts to make predictions from seasons to many decades into the future. Given the complexity and momentum of human activities and environmental processes, the effort to make predictions is truly one of the most challenging intellectual undertakings facing us. While progress can be expected to be slow, the choice of not seeking to understand the full implications of present and future human development activities would doom us to continual surprises for which the costs of responding would likely be large. It is in this light that we undertake efforts to predict the future climate.

While we can learn much about the behavior of the Earth system by examining how it has behaved in the recent and geological past, there has been no time in the past (except for the catastrophic conditions following major asteroid impacts) when the change in atmospheric composition has occurred as rapidly as it is being affected by human activities today. For this reason, and others, the past can provide insight about what factors will change the climate and by roughly how much, but cannot be used to project conditions into the future. For that, our only tool is to combine as much of our current understanding as we can into comprehensive numerical models of the Earth system and then to use these models (referred to as GCMs) to conduct "experiments" on what can be expected to happen in the event of, for example, tropical deforestation or unrestrained use of coal, oil, and natural gas, or widespread changes in land use through agricultural expansion or reforestation.

Ideally, models are the only viable tool for such efforts, taking up where human minds become limited, by being able to incorporate as many of the interacting processes and influences as are understood in a quantitative manner that subdivides the world into tens of thousands of finite domains and that does not leave out what may incorrectly be thought to be minor influences which can have amplifying or moderating effects. While computers can do the needed hundreds of trillions of calculations that are necessary, scientists are careful to make sure they understand what is happening before they place high confidence in model results. To help in this process, the model experiments provide vast amounts of data to help understand how well models are matching real world behavior, why changes and events are occurring, whether the events were a result of human activities or simply natural fluctuations, and whether the results are dependent on aspects of the Earth system behavior that we understand well (and so should have high confidence in) or aspects that are relatively uncertain and not in accord with records of past climatic behavior (in which case we should withhold our confidence and focus our attention on research to further our understanding of the model results and to make indicated improvements).

See comment 1.

Important examples of where GCMs in the United States and in other nations have demonstrated increasing skill are in their ability to represent seasonal changes in climate, to represent the departures from the normal seasonal to interannual pattern of changes in the low latitudes where the El Nino cycle increases eastern Pacific Ocean surface temperatures, to represent the few year cooling and subsequent recovery following major volcanic eruptions such as Mt. Pinatubo in 1991, to represent the climates of periods in the geologic past that had significantly warmer or colder climates, and to represent the recent gradual warming that may be attributable to human activities.

Gaining an Understanding of Model Results

Models are a tool for helping scientists understand what is happening. The results of models are evaluated in the context of all that is understood about Earth system behavior. One step in the process of gaining acceptance of model results is the publication of peer-reviewed journal articles describing the results, a very rigorous process that both forces careful analysis by the model developers and calls into question those results where models and observations do not match. The progress of science is slowed when those putting forth and those criticizing model results do not equally participate in this process.

To achieve a synthesizing of scientific understanding that considers results from all sides of the spectrum, various bodies convene review and assessment panels. Most prominent internationally is the Intergovernmental Panel on Climate Change (IPCC) which periodically publishes assessment reports that are drafted by an international team of expert authors, reviewed by an international array of scientific experts, and then reviewed by the countries of the world, each responsible for organizing their own review effort. Preparation of the Second (pentadal) IPCC Assessment is underway, and the United States country review process has involved hundreds of invited expert scientists (spanning a wide range of perspectives on the issues), agency program leaders, and stakeholders from industrial and environmental groups. The IPCC and other reviews, for example by the National Academy of Sciences, provide a highly considered analysis of the state of scientific understanding and deserve great weight by decision makers.

Independent evaluations of the scientific results are another means for gaining understanding; however, they are often difficult to perform well and completely due to the wide range of knowledge needed and the limited time to pursue the process. This GAO report is an example of an effort for an independent analysis. Based on the request from Congressman Dingell, the GAO has investigated and analyzed research underway regarding GCMs in order to provide an enumeration of present limitations in the best available models. While

See comment 1.

we have no significant difference with the GAO analysis in response to the very specific request, the U. S. Government's modeling agencies believe that contemporaneously providing a summary of what models do well is needed in order to provide perspective on understanding where science stands in making useful projections about future conditions.

What Models Are Projecting for the Future

To help focus in particular on the performance of models in support of the GAO study (and for other reasons), the Subcommittee on Global Change Research convened a group of scientists ranging from modelers to model critics and asked them to attempt to provide a consensus summarization of the current state of scientific understanding. While some doubted that this could be achieved, it has been accomplished. In brief, the group of scientists (after considerable discussion and written reviews, but ultimately without recorded dissent) agreed upon a series of statements with the appropriate degree of confidence indicated and that are supported both by model results and by overall scientific understanding. The resulting statement of the participants in the USGCRP Model Forum has just been published (in slightly condensed form) in EOS (the transactions of the American Geophysical Union) and is being published in full by the U. S. Global Change Research Program (a prepublication draft that may be released is included as an appendix to this response).

Extracting from the full report (which should be read in full to appreciate the basis for the statement), the scientists agree that:

- Human activities are increasing atmospheric concentrations of gases and this will enhance the natural greenhouse warming effect,
- Aerosol concentrations are increased due to human activities and they can exert a cooling influence on climate,
- Greenhouse gases (but not the aerosols) are generally long-lived in the atmosphere and the Earth will thus have a prolonged warming influence from human activities,
- Projected emissions of these gases will increase their concentrations significantly in the future,
- Stratospheric cooling and surface warming to be expected from past emissions of gases and aerosols have already started,
- Further warming over the next century is very probably in the range of 0.5 to 2 C (1 to 4 F),
- Sea level will very probably rise at an accelerating rate,
- Global precipitation and evaporation will increase but not uniformly everywhere,
- Arctic lands will very probably experience an amplified winter warming and mid-latitude continents will probably experience drier summer conditions,
- Changes in climate variability (including changes in tropical storm intensity) are possible but too uncertain to specify,
- Details of changes over the next 25 years are uncertain due to possible natural variations in the climate, and
- Biospheric feedbacks omitted from the models, while uncertain, could somewhat amplify or moderate the changes.

This set of statements indicates that significant progress in understanding has been made over the past decade; however, there was agreement that, while progress will be occurring each year, it will require another decade and more of research to significantly improve confidence in the projected regional details of the anticipated changes. The participants then pointed out nine specific opportunities where sustained or intensified research would bring important gains in understanding and predictive capabilities, a set that is closely related to the set of limiting uncertainties identified in the GAO report.

USGCRP Research on GAO-Identified Limiting Uncertainties

The USGCRP goal is to improve predictive understanding of the Earth system. Its research program is thus focused on reducing the limitations that restrict the abilities of models to make more accurate projections. In particular, significant resources are being devoted to removing and reducing the limitations identified by the GAO. We would offer the following comments on what we are doing to respond for each of the limitations identified by the GAO (we would note that the identified set of limitations is somewhat overlapping, and the set of USGCRP responses and activities is similarly so).

See comment 3.

1. Inadequate Representation of Processes Affecting the Climate. The USGCRP is devoting approximately 30% of its $1.8B budget to conducting research aimed at improving scientific understanding of processes controlling and influencing the climate. Process studies, which are generally conducted with international cooperation, include major studies to understand the global water cycle, ocean circulation, cloud-radiation interactions, land surface processes, atmospheric chemistry, and other processes. In addition, the USGCRP is supporting a series of model intercomparison studies to improve understanding of how well models represent the present climate and, thereby, to identify which processes are not adequately represented and on which research should be focused. An important recent accomplishment in the development of models that more adequately represent Earth system processes is the development of the second generation Community Climate Model (CCM2) at the National Center for Atmospheric Research.

See comment 3.

2. Exclusion of Critical Processes. It is important to understand that not all processes are equally important; most models include all of the processes that are most important, including radiation, water vapor, convection, sea ice, land surface exchanges, and many more. The USGCRP is supporting efforts by major modeling groups to include an even more complete set of processes in their models and is supporting a major international model intercomparison project (AMIP) to identify systematic errors in GCMs. Processes now receiving attention include sulfur aerosols, cloud water and cloud microphysics, surface exchange processes including vegetation, and horizontal and vertical mixing in the oceans. Substantial progress is now being made toward accurate simulation of longer term climate components, particularly the deep ocean, sea-ice, and terrestrial vegetation. A new global ocean model developed through an unprecedented collaborative effort among NCAR, the Naval Postgraduate School, and the Los Alamos National Laboratory has a resolution of less than 20 km (about 13 miles), which results in a significantly improved representation of oceanic heat transport. When coupled to improved atmospheric models (e.g., CCM2), significant improvements in long-term simulations will be realized.

There also remain critical biospheric and chemical interactions to include. In addition, and not mentioned specifically in the GAO report, it is essential to fully represent land and cryospheric components and their interactions in climate models. The USGCRP is moving actively to support such efforts.

See comment 3.

3. Inadequate Representations of Interactions Among Variables [the text actually refers to Earth system components rather than variables]. The USGCRP is strengthening efforts to couple models of the atmosphere, the oceans, sea ice, and the land surface in order to provide models that can adequately represent the exchanges of fluxes which couple the system components. It is essential that all of these components, including also land glaciers, be represented in simulations of the long-term climate. Two specific examples of USGCRP efforts include the Climate System Modeling program of NSF and the Earth system modeling program of EPA.

See comment 3.

4. Inadequate Representations of or Accounting for Feedback Mechanisms. Present models include representations of many of the most important feedbacks, but more and more intense observational studies are indicating shortcomings that currently are present in the parameterizations. As indicated in response to the first point, the USGCRP is devoting about 30% of its budget to improving understanding of processes and feedback mechanisms. As one example, a number of programs are underway to better understand the role of cloud-radiation interactions, particularly as they relate to absorption of solar radiation, cloud changes in height and extent as climate changes, etc. The USGCRP is also studying past climatic conditions as a means of trying to identify potential surprises and changes that nature may have hidden from those studying the present climate.

See comment 3.

5. Insufficient Computer Power. The Earth system is large and complex, with processes taking place on spatial scales from the microscopic to the global and on temporal scales from seconds to centuries (and beyond). Representing the necessary elements of this system needed to make projections of future climate requires extensive computer resources. While it does no good to compute when processes are not well enough understood, we understand enough about the most important processes to make informative calculations that are significantly beyond the computer resources that are currently available for this purpose. More computing power is needed not only for storing and analyzing vast amount of data but also for running high resolution GCMs for long-term simulations, and doing so multiple times to improve the statistical validity of the results. Such long-time simulations are needed to test how well the interannual to decadal variabilites are simulated, to test the climate changes under various scenarios (e.g., doubled carbon dioxide), and to carry out predictability studies for various forcing sensitivities.

To address the near-term problem, the USGCRP through NSF has established a special-use, dedicated climate system modeling computing facility known as the Climate Simulation Laboratory (CSL) in cooperation with NCAR. This facility will provide state-of-the-art computer resources and data storage systems for use in major modeling research simulations, especially those that will support the IPCC and other assessment efforts where computer resources are short. The facility is open to all investigators funded or supported by a U.S. university or federal or private not-for-profit laboratory. The CSL encourages simulations of multi-100-year runs with coupled climate models and very large ensembles of seasonal to interannual predictability runs. For the longer-term, DOE's CHAMMP program is already making progress in overcoming the challenges of using the new massively parallel computers(with their promise of greatly reduced cost per compute cycle) to address the climate issue.

See comment 3.

6. Cold Start Error. There are three causes of the "cold start" error. One is that we do not have detailed observations of the oceans back in time as we do for the atmosphere; as a result, we can only start with conditions that approximate the actual conditions in the oceans at various times in the past. A second cause of the "cold start" error is the lack of understanding of ocean and atmospheric processes. To help alleviate these problems, the USGCRP is supporting, along with other nations, major field programs to observe and understand the oceans. New data sets, such as that from the TOPEX/POSEIDON satellite, will enable more realistic initialization of the global ocean, a major factor in "cold start" errors. The third cause of the "cold start" error is the unavailability of adequate computer resources. With adequate physical and spatial representation of the oceans and with the ability to carry out very long simulations, scientists will be better able to reduce the problem. Already, models with finer spatial resolutions are showing reduced flux imbalances between the atmosphere and oceans and this will help in not exacerbating the cold start problem.

See comment 3.

7. Inability to Project Regional Changes in Climate. The ultimate goal of the USGCRP is to be able to project climatic changes on scales of interest to those evaluating the risks and benefits of climatic change. Achieving regional resolution in climate models requires both incorporation of additional processes and significantly increased computer resources (requirements increase by about a factor of ten for each halving of the spatial resolution).

As indicated above, the USGCRP is supporting both process research to improve understanding of what processes must be treated and to provide increased computer resources. As a result of these efforts, models are beginning to show improved representations of regional features over subcontinental areas such as the Sahel and the central United States.

In addition, to begin to explore regional changes, the USGCRP is supporting use of high-resolution, sub-continental scale models to look at domains such as the western United States. Such models cannot be run very long times, so do not yet provide climatic information but do provide some indications of how specific global climate changes may be manifested at the regional scale.

Summary

Overall, the USGCRP finds the GAO report an interesting and useful perspective on the most important factors limiting the credibility of the results of GCMs. At the same time, there are many important successes of GCMs that give credibility to major aspects of their results. We have attempted to describe these as well as the steps we are taking to address the important scientific limitations identified by the GAO in its report.

GAO Comments

The following are GAO's comments on the Subcommittee on Global Change Research's letter dated May 22, 1995.

1. Under the heading "Factors Limiting the Accuracy of Models' Estimates," we discussed some of the successes of GCMS to create a context and provide balance for our discussion of the models' limitations. Later, under the heading "Improving GCMS' Estimates," we discussed the efforts that are currently under way to address these limitations and referred to the agencies' discussion of such activities in this letter. Under the heading "Agency Comments," we explained why we did not reproduce the report of the U.S. Global Change Model Forum in this report.

2. We added a footnote on page 3 of the report to better explain USGCRP's role in coordinating federal research on global climate change.

3. We revised our discussion of the models' limitations (pp. 8-14 of our draft report) as necessary to address the agencies' specific comments. We changed the heading "Exclusion of Critical Processes," cited in the agencies' comments, to "Some Processes Not Included or Fully Incorporated in Some Models" to better describe the supporting text.

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