Models for the global climate change

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The purpose of this paper is to show:

1. How the climate is changing
2. To discuss some mathematical models which show how the climate is changing
3. To indicate the rates at which the changes are occurring
4. To discuss what are the implications for the future
5. To indicate some of the actions necessary to be taken

How the climate is changing

The Earth's climate is changing. The global mean temperatures are rising. For example the year 1995 was the warmest on record and the last 10 years (1987 - 1996) were the warmest ten years on record. Glaciers are melting almost everywhere and are disappearing in many parts of the tropics. At the same time the composition of the atmosphere is changing, with clear evidence for increases in carbon dioxide concentrations. It is now well established that these increases are due to human activities through the burning of fossil fuels and deforestation. A central question then is whether the climate changes and global increases in temperature are caused by the human-induced effects. And do they matter?

Some degree of global warming now seems certain. Thus, adaptations to climate change will be required, such as housing designs that enhance summer-time cooling, the "greening" of inner cities, the strengthening of coastal buffers and improved control of vector-borne and water-borne diseases. Health-indicator monitoring and disease surveillance should be integrated into the 3 nascent global observing systems for world climate, oceans and terrestrial systems.64 Multidisciplinary research into the identification, understanding and modelling of health impacts needs support, as do intergovernmental and interagency collaborations to develop health early warning systems that can facilitate timely, environmentally friendly public health interventions. Recognizing the wide-ranging potential consequences of climate change for our health and well-being can greatly strengthen the international rationale for reducing greenhouse gas emissions. Although there is much that is unavoidably complex and uncertain about these large-scale risks to human population health, the case for health professionals urging a health-protecting, precautionary approach that will have multiple health benefits remains clear.

The impact on climate changes

Changes in global climate would significantly affect human health, natural aquatic and terrestrial ecosystems, and agricultural ecosystems. World-wide attention recently has turned to these issues and scientists from many disciplines and many countries are working to assess the potential magnitude and direction of the changes and the risks to the biota. Of great immediate concern to policy makers and scientists worldwide, are the potential effects of the changes on the world's agriculture. To meet the demands of a growing human population, agricultural productivity must continue to increase. If global climate changes, act to reduce food production, serious, long-term food shortages and aggravation of societal problems could result.

Modelling the effects of climate change

Complex, integrated mathematical models are used to estimate the likely effects of climate change on vector-borne diseases. These highly aggregated models are in the early stages of development and do not take into account local environmental and ecological circumstances. Nevertheless, they are useful for forecasting the broad direction and potential magnitude of future change.

Such models project substantial increases in the transmission of malaria and dengue fever worldwide and a decrease in the transmissibility of schistosomiasis because of excessive warming of water and some regional drying. Conditions conducive to malaria transmission, for example, are expected to increase from a doubling of atmospheric carbon dioxide. The majority of computer projections indicate some increase in malaria transmissibility in response to standard scenarios of climate change. The actual changes in the incidence of malaria and dengue fever would, of course, depend on many factors, including future patterns of social development, land use and urban growth, and the effectiveness of preventive measures such as vector control and vaccination.

The growth of algae in surface waters, estuaries and coastal waters is sensitive to temperature. About 40 of the 5000 species of marine phytoplankton (algae) can produce biotoxins, which may reach human consumers through shellfish. Warmer sea temperatures can encourage a shift in species composition of algae toward the more toxic dinoflagellates.48 Upsurges of toxic phytoplankton blooms in Asia are strongly correlated with the ENSO cycle. It is also apparent that algal blooms potentiate the transmission of cholera.

Electron microscopy has shown that algae and the zooplankton that feed upon them provide a natural refuge for Vibrio cholerae, where, under normal conditions, the bacteria exist in a nonculturable, dormant state. An increase in sea surface temperature, along with high nutrient levels (eutrophication) that stimulate algal growth and deplete oxygen, can activate the blooms and vibrios.

Sea surface temperature in the Bay of Bengal is correlated with algal blooms and outbreaks of cholera in Bangladesh.50 Climate variability and change may thus influence the introduction of cholera into coastal populations. V. cholerae occur in the Gulf of Mexico and along the east coast of North America.

Heavy rainfall may cause outbreaks of cryptosporidiosis, which causes severe diarrhea in children and can cause death in immunocompromised individuals.

Rodent populations are also influenced by climate anomalies. Prolonged droughts deplete rodent predators (owls, snakes and coyotes), whereas rains provide new food supplies. These dynamics apparently contributed to the 1993 outbreak of hantavirus pulmonary syndrome in the southwestern United States and may have contributed to recent outbreaks of that disease in Argentina, Bolivia, Chile, Canada and Paraguay.

Lyme disease is also important in North America. Large deer populations (with few predators) and warm winters allowing overwintering of tick populations at higher latitudes37,57 could increase the range of the disease.

Climate change could also affect food production, with declines concentrated in low-latitude regions, where food insecurity often already exists, including Africa, the Middle East and India. There is a range of estimates of the risk of hunger reflecting different assumptions about future population growth, international trade and adaptive agricultural technology. Such estimates, however, do not include the likely additional influence of extreme weather events or of increases in agricultural pests and pathogens.

Accelerated rise in sea level would have a variety of health impacts. The Intergovernmental Panel on Climate Change has forecasted a rise of about 40 cm by 2100.1 With unmitigated emissions of greenhouse gases by 2080, the number of people flooded annually would increase from 13 million to 94 million: 60% in South Asia and 20% in Southeast Asia.2 Populations on low-lying islands such as the Maldives, the Marshall Islands, Kiribati and Tonga, and in the deltaic regions of parts of Africa and the United States, would also be vulnerable to accelerated rises in sea level and associated increases in storm surges. Salination of coastal farmlands and of freshwater aquifers would cause economic disruption, population displacement and additional adverse health consequences.

In Canada, much of the coast of Prince Edward Island is highly erodable, and shorefront buildings may be threatened along the Gulf of St. Lawrence. Rises in sea level and increased storm surges along the tundra coast of Alaska and Canada are likely to cause erosion and flooding.60 The Arctic and the Antarctic are, in general, likely to be particularly vulnerable to climate change, resulting, for example, in substantial loss of sea ice and changes in species composition, with implications for indigenous communities following traditional lifestyles. In addition, loss of ice cover will alter the Earth's albedo (reflectivity), thus increasing heat absorption and contributing to climate change.

Climate Models: How Reliable are Their Predictions?

We often hear the assertion that our extensive use of carbon- based fuels now threatens to alter the climate of the whole world: that enhanced greenhouse warming induced by the carbon dioxide and other gases we have added to the air will lead to a rapid and unprecedented rise in the average temperature of the Earth within the next fifty years.

We are not accustomed to long-term forecasts of anything of such consequence. Nor can it be surprising that the initial reaction of almost anyone is to question the reliability of the prediction. For what is claimed--if indeed an accurate portrayal of the future seems to leave few choices: do we prepare ourselves for the impacts of lasting climate change? Should we rethink our own use of coal and oil and natural gas and gasoline, when energy use, as we all know, is very much tied to economic growth?

What must trouble many decision-makers is that the sounding of this loud environmental alarm was tripped not so much by measurements as by computer models. How certain or how controversial are these largely theoretical predictions of global warming, and on what assumptions are they based? Given the potential importance of regional climate changes for the development of national policies, and the impacts of extreme, climate-related weather events such as droughts, floods, and hurricanes on agriculture and human safety, how reliable are the projections of future change? Are the uncertainties in present climate models so great that we can ignore their predictions? What elements are the most robust? What are the prospects for substantial improvements in climate models in the near future?

These questions, so often asked, were put to a group of scientists in late 1994 in response to requests from both the White House Office of Science and Technology Policy (OSTP) and from the Government Accounting Office (GAO) which was responding, in turn, to a request from Congressmen John Dingell of Michigan. The charge to the Forum, which I chaired at the request of the U.S. Global Change Research Program, was to develop a statement on the credibility of modeled projections of climate change, to provide background to the government for considering and developing national policy options. The participants included climate modelers and other knowledgeable scientists who were chosen to bring to the Forum a wide spectrum of scientific opinion regarding the potential threat of global greenhouse warming. This review provides the author's summary of the Forum report, which is listed as a reference at the end of the article.

General circulation models

Computer-run, mathematical simulations or models of the atmosphere and ocean are the principal tool for predicting the response of the climate to increases in greenhouse gases. The most sophisticated of these, called general circulation models, or GCMs, express in mathematical form what is known of the processes that dictate the behavior of the atmosphere and the ocean. GCMs include the interaction of the atmosphere with the oceans and with the surface of the Earth, including plants and other ground cover. They allow us to test, by mathematical simulation, what should happen to climate, around the world, in response to a wide variety of changes. For example, what climatic effects would follow a major volcanic eruption, or a change in the radiation from the Sun?

The great power of mathematical models lies in their ability to simulate the behavior of systems--like the atmosphere and ocean that are too complex or extensive for simple, intuitive reasoning. There are limits, however, to how much complexity can be handled by the computers on which the models are run. At present, models of the global climate system cannot include physical processes whose horizontal dimensions are less than several hundred miles--a constraint that imposes simplifications on how well we can model what we know and restrictions on the level of regional detail. The key is to incorporate the best possible representation of all the important processes and feedbacks necessary to characterize the climate system, while keeping within the practical capabilities of modern computers.

Our ability to evaluate the strengths and weaknesses of climate models has grown over the last two decades. A growing number of GCMs, many with independently derived components, are available for intercomparison. We have a growing store of meteorological and oceanic observations against which model predictions can be tested. We also have information on past climate change, recorded by natural processes in rocks and sediments, that allow us to assess the ability of models to replicate the known features of climates different from that of the present day. Each of these elements is the basis for debate on the reliability of climate model projections of the future climate.

Consensus predictions

All of the global climate changes experiments designed to assess the impact of increases of greenhouse gases point to global warming through the coming century, with accompanying changes in rainfall and other meteorological quantities. Still, the complexity of the climate system is a tremendous obstacle to predicting future climate change. Neither climatological observations nor present climate models is sufficient to project how climate will change with certainty. A workable approach is that adopted by the Intergovernmental Panel on Climate Change (IPCC) of the World Meteorological Organization and the United Nations Environment Programme, which is based on projections of the expected growth of greenhouse gases and the combined results of many GCMs. In terms of mean global surface temperature, the consensus prediction of the IPCC is for an increase of 0.5 to 2 ° Centigrade (about 1 to 3.5 ° Fahrenheit) by the year 2050, in response to an anticipated increase of 1 percent per year in CO2. The low end is a significant change; the high end, a dramatic one. Moreover, were the amount of atmospheric carbon dioxide to double, the consensus forecast is for an eventual warming of 1.5 to 4.5 ° C (about 3 to 8 ° F.)

Such changes, if realized, would represent a significant climatic change. For example, the most recent climate change of similar magnitude was the last major Ice Age that reached its peak about 18,000 years ago. The mean global temperature during that time is estimated to have been between 3 and 4 ° C cooler than at present. The effect of this small a change in global-mean temperature can be appreciated when we realize that during the last Ice Age, glacial ice--a mile or more deep--covered much of North America, year-round, reaching as far south as the Great Lakes and the surrounding states of present-day America. That amount of change in global-mean temperature is similar, although opposite in sign, to what is now projected due to increases in greenhouse gases. But the rate of change is not. The last Ice Age developed over thousands of years, while global greenhouse warming is projected to occur within a span of less than a century. And within the lifetime of people now living.

It is equally clear that in terms of potential impact, the difference between a 1.5 ° and a 4.5 ° C projection for future warming is very large. As a result of this uncertainty, decision- makers are confronted with a difficult question. What steps should be taken when the best indications from state-of-the-science models suggest that climate change due to human activities may be large and significant, yet the predictions are less than certain?

The scientific debate regarding these uncertainties has entered the public arena, providing considerable confusion even for those aspects of climate-model predictions that are virtually certain. The debate over how much warming--and by when, and why it hasn't yet been more clearly seen--has clouded the clearer picture that increases in carbon dioxide will increase the global-mean temperature.

It has also affixed the stamp of "controversial" on almost any reference to impending global warming in the press and news media, implying, erroneously, that the general concept, and not just the details, is in serious doubt.

It is possible to get an indication of the strength of a building or other structure if we know which of its footings are solid and which are less so: in this case, to separate the aspects of predicted climate change that are virtually certain from those that are uncertain. The Forum carried out this kind of assessment of predicted global warming, to provide better illumination for policy discussions and to assist policy development.

The evaluation is divided into three parts. The first provides a basis for any discussion of climate-model predictions by identifying the foundations of the greenhouse warming theory that are most solid and robust: a series of conclusions which can be viewed as "virtually certain" based on observations, experiments, and the results of many models. The second part is a listing of specific predictions of climate models that are societally important, ranked by degree of certainty. In the last part we examine what can be done in the future to improve climate-model predictions.

Global Climate Modeling:

Introduction

Global climate science has progressed significantly in recent years but our lack of knowledge is still great. A major vehicle for understanding the enormously complex global climate system has been computer modeling. Today's GCMs have developed rapidly relative to earlier models and provide improved estimates of what may happen in the future. Many believe that such models are still in a relatively early stage of development. Nevertheless, GCMs are important research tools that can help to focus the research and measurements needed to better understand climate change. Climate modeling will be increasingly more valuable as models and our understanding of basic processes are improved.

Models of climate changes are still evolving because we do not yet completely understand or model everything that can or will affect climate. Scientific uncertainty will always be a component of modeling climate change. Our challenge is to reduce this uncertainty. Because of the Uncertainty, Care Must Be Used in Decision-Making Care must be taken when using the results of climate models for major public policy decisions because of the existing uncertainty, as well as our lack of knowledge about important physical and chemical reactions in the atmosphere and oceans.

Adapt Via "Act-Learn-Act"

Because man-made greenhouse gas emissions are likely to continue to increase in the future, is necessary to search for adaptive and affordable management strategies, such as "act-learn-act," that are robust against what we do no yet know. We will surely be learning more about climate change over time. As we learn more, we must revisit greenhouse-related policies and adjust them accordingly.

The public's and decision-makers' understanding of the strengths and weaknesses of computer modeling of global climate is essential to the formulation of long-term policies related to global climate change.

The majority of the specialists on this general subject agree that:

- There are a number of "greenhouse" gases in the earth’s atmosphere, including water, in the form of vapor, CO2, and methane. (Water vapor is a much stronger contributor to the natural [non-anthropogenic] greenhouse effect than CO2.)

- Atmospheric carbon dioxide (CO2) has been increasing for more than 100 years, almost certainly in large part because of human activity.

There are growing indications that global near-surface temperatures have increased over the past century by about 1°F (0.6°C). Temperatures in the lower five miles of the atmosphere, the lower-to-mid troposphere, have increased only slightly, if at all, in the past several decades of instrumental monitoring.

- Natural increases in atmospheric CO2 in the Earth's past have been well documented, however, the cause-and-effect relationships with past climate change are not clear.

- The rate of increase of CO2 in the atmosphere in the past century is greater than any previously recorded historic rate.

- How much of the observed warming is caused by human activities and by natural climate variations is uncertain.

Climate data are highly variable ("noisy") in space and time. Accordingly, it is very difficult to extract subtle changes from short-term trends in climate data. It is only because the warming trend in globally averaged surface air temperature has risen above the "noise" that it has been detected.

Climate Modeling and Simulation

How can we understand the earth's climate system and the possible consequences of increased concentrations of greenhouse-gases in the atmosphere? We can do some things in the laboratory, but because the earth's climate system is so large and incredibly complex, we can recreate only small pieces of it in the lab for extensive study. So scientists develop computer models based on the governing physical principles as expressed by mathematical equations that describe many of the processes that may affect climate. Such models act as simulation laboratories in which experiments can be performed that test various assumptions and combinations of events. These experiments not only can expand our knowledge, they can also develop insights into possible climate futures. Although there are a variety of increasingly complex climate models, only the "general circulation model" (GCM, sometimes also referred to as a global climate model) determines the horizontal (geographical) and vertical (atmospheric and oceanic) distributions of a group of climatic quantities, including

1. temperature, wind, water vapor, clouds and precipitation in the atmosphere;
2. soil moisture, soil temperature and evaporation on the land;
3. temperature, currents, salinity and sea ice in the ocean.

The related equations are so complex, however, that they can only be solved for specific geographical and vertical locations, and only over specific time intervals. For example, a typical GCM subdivides the atmosphere into thousands of three-dimensional volumes, each having linear dimensions of about 250 miles in the north-south and east-west directions, and a mile in the vertical direction. The task of making these boxes smaller is severely limited by the speed of even present-day supercomputers. For example, decreasing the horizontal size of a GCM from 250 to 25 miles would increase the required computer running time by a thousand fold -- from about 2 weeks to more than 30 years of run-time to compute the resulting change in the equilibrium climate of the model!

The Uses of Climate Models

Until the advent of supercomputers, our attempts at climate modeling were rudimentary. That situation changed roughly 25 years ago. Much of the recent attention by the public and decision-makers on climate change has been due to measurements indicating that warming has been occurring near the

Earth's surface over the last century and to relatively recent projections from GCMs.

Climate varies naturally over both short and long time scales, sometimes rather dramatically over a few years or decades. This rapid variability was experienced in Europe during the Little Ice Age of 1400-1850. To understand climate change, scientists must understand the detailed nature of the extremely complex climate system. While we have learned a great deal, there is still much we do not know. Climate models today can give us insights into what might happen under various assumed situations.

Currently, there are about 30 GCMs being developed and/or used by research groups around the world. Many of these models are related, with the differences among the models lying in the natural processes they include and how they integrate and treat these processes within a specific model.

As discussed above, computer models are necessary in the study of climate change because of the extraordinary complexity and number of the physical processes that are embodied in the climate system. Some of the factors that affect climate include:

- the concentrations of gases and aerosols;
- interactions between the atmosphere, the biosphere, and oceans;
- volcanic activity;
- interactions of components within the atmosphere and ocean themselves.

The growth of computing capacity has allowed scientists to integrate complex climate-system processes into single computational frameworks. These frameworks can be used to develop an increasingly more comprehensive, but still incomplete, overall picture of the global climate system.

The Roles of GCMs

The general uses of GCMs are:

1. First, the building and running of a model is a process by which theory and observations are mathematically evaluated, codified and integrated in a computer program. Models can thereby be used to identify needed refinements in theory and observation. Model building is a long process of back and forth comparisons between analytical description ("theory") and field studies ("observational data"). These comparisons include end-to-end efforts to correlate observational findings with improvements in model representations.

2. Second, climate models are used to identify and then assimilate observational measurements that are initially incomplete. These measurements can then be used to derive more consistent, spatially specific estimates of meteorological quantities. Such model-assimilated data have proven to be of great utility to the research community in better understanding the observed and potential variability of the climate system.

3. Third, models can be used to focus observational activities. In regions where data are sparse, models can be used to define the frequency, coverage, and type of measurements that may shed the most light on the physics, chemistry and the composition of the atmosphere.

4. Fourth, climate models have recently predicted a few climate anomalies up to a year in advance. These model predictions, which are increasing in accuracy, incorporate information on the current state of the oceans and atmosphere. Predictions of El Niño and La Niña events and climate anomaly patterns associated with these phenomena have proven reasonably accurate and there is potential for this type of model prediction to be extended out beyond a year.

5. Fifth, climate models can be used to develop scenarios of possible future states of the climate system, given a specified set of assumptions (e.g., the future quantities of greenhouse gases, including ozone trends and aerosols). Such climate scenarios can then be used to develop projections of possible climate-related impacts on human and natural systems. Models currently show large-scale climatic response to increased greenhouse gas levels: for instance,

(1) there may be some warming at the surface, warming of the troposphere, and some cooling in the stratosphere;

(2) there may be greater warming at high latitudes than at low latitudes;

(3) there may be an increase in low level humidity over the oceans. Such fingerprints of human-induced climate change have been compared with the observed climate to help detect its changes and attribute its causes.

From the GCM-based projections of climate change, analysts can begin to evaluate the potential impacts on market and non-market sectors of society. As these impact models become more sophisticated, increasingly better pictures of what might happen under different scenarios will develop. More research on impacts will help countries identify the seriousness of possible climate change and allow them to study the cost-benefits of various response options.

In addition, models can be used to facilitate an understanding of the lag time between causes and effects associated with human as well as natural causes of climate change. It is essential to keep in mind that model projections depend on the sophistication of the model: the estimates in the model, the assumptions used by the model, and what in nature is not yet understood and therefore not covered in the model. This is why the climate research community generally places so much emphasis on verifying model results with actual data. By exploring sets of these model projections, the policy community can begin to discuss the effects that policies, aimed at reducing greenhouse gases, might have on climate, humans, and economies.

Models & Decision-Making

Existing GCMs can make "what if" projections of future global climate possibilities because they are the best available tools, even though they are currently limited in resolution and completeness.
Regionally specific information is ultimately needed because, for example, while U.S. citizens have interest in what happens to the planet as a whole, they are especially interested in what happens to the U.S. and to their own neighborhood. Global climate projections from different models show a range of effects. The range of effects is largest for smaller regions. Partly, this is due to the natural local variability of climate and partly this is due to scientific uncertainties.

Just as global climate models have advanced, so have global economic impact models for estimating costs and benefits. Integrated assessment models, which take into account chains of events (if "A" happens, then results "B" could occur, but if "A" does not happen, then "C" will occur), are a tool to help understand long-term costs and benefits.

Limitations of Models

Having discussed the uses and strengths of GCMs, one should not assume that they do not have weaknesses--in fact, some scientists would state that the weaknesses are so great as to question their value in near-term decision-making. Some of the features of the GCMs are less robust than others, partly because there is disagreement between the models about predicted climate changes. Furthermore, even if the models agreed, it does not necessarily make them correct.

Phenomenological Feedbacks

Much of the uncertainty in current climate models is associated with "feedbacks" – how various phenomena interact with one another. Feedback mechanisms are clearly important. Climatologists agree that, without these feedbacks, a doubling of CO_2 would give about a 1.8°F (1°C) rise in global-average temperature. Many phenomena have large impacts on others, some amplifying and some dampening effects. Some extremely important phenomena, the feedback consequences of which we do not yet fully understand, are the following: clouds, ice, land surface processes, ocean effects, biological processes, physical and chemical reactions in the atmosphere, particulates, solar cycle effects and tropical convection and rainfall.

These phenomena are not yet adequately understood in isolation, let alone in combination with other factors. Thus, scientists must utilize approximations, estimates of aggregate regional effects, or ignore some phenomena all together for the time being. Other suspected feedback mechanisms are yet to be described or modeled. For example, the role of clouds and water vapor in climate models is not well understood; yet water vapor is the most significant greenhouse gas in the natural (unperturbed) atmosphere and dramatically affects cloud cover and the transfer of radiant energy to and from the Earth's surface. Also, modeling the impact of clouds is difficult because of their complexity and compensatory effects on both weather and climate. Clouds can reflect incoming sunlight and therefore contribute to cooling, but they also absorb infrared radiation that would otherwise leave the earth, thereby contributing to warming.

Parameters

Models utilize observational data to adjust various model parameters to help make such parameters more realistic. "Tuned" models, however, cannot be validated by the data for which they were adjusted and must be validated by independent means. As previously mentioned, the equations related to the climate to be modeled are so complex that they can only be solved at specific geographical and vertical locations, and only over specific time intervals. The limit on horizontal size imposed by present-day supercomputers also limits the physical processes that can be explicitly included in a GCM. As discussed above, GCMs using today's supercomputers explicitly include physical processes having horizontal sizes of approximately 250 miles and larger. Worse yet, the physical processes smaller than 250 miles cannot be ignored because their effects can significantly impact climate and climate change. Thus, climate modelers face the dilemma that their models cannot resolve the small-scale physical processes and they cannot ignore their effects. This is one, if not the major difficulty in modeling the Earth's climate. The approach taken to overcome this problem is to determine the effects of the small-scale physical processes on the larger scales that can be included in a GCM using information on those larger scales and statistical relationships. This approach is called "parameterization." The principal differences among GCMs lie in their approaches to parameterization, particularly in the case of cloud and precipitation processes. These parameterization differences have a significant influence on differences in climate sensitivity – the change in the equilibrium global-mean surface temperature resulting from a doubling of the CO_2 concentration – between various GCMs.

Testing Models

One way that models are tested is to use them to reproduce past events and variations. The earth's climate has been changing for millions of years but we do not have detailed data on those changes because humankind was not acquiring relevant data until relatively recently. As such, we cannot accurately truth test climate models over past periods of time beyond much more than a hundred years. Thus, we are asking these models to assist us in decision-making in an environment of considerable scientific uncertainty. There is, however, significant effort underway to compare the general nature of model simulations of pre-historic time periods against data from proxies (e.g., tree-ring widths, borehole temperatures, and oxygen isotopes in sediments) of past climates.

Human Resources

Compared to intermediate and smaller modeling efforts, such as those aimed at understanding the behavior of a particular climate process over a single locality, insufficient U.S. and international resources for research and computer hardware are being devoted to high-resolution global climate modeling.

Data

Instrumental temperature measurements of varying quality exist for about 135 years. Relatively crude but useful information before then has been obtained from proxy data such as the width of tree rings and the abundance of certain isotopes trapped in ice cores taken from the ice caps and glaciers and in sediment cores taken from the deep sea and lakes.

Climate data are routinely collected for weather prediction. Much of this data gathering was not designed to detect subtle trends that occur on decadal or longer time scales. For climate modeling, we need more accurate and extensive data than even currently used in weather prediction. There is also a need for better organization and long-term archiving of climate data.

Advancement of Models

Model development has progressed considerably in the past decade. However, though there have been downward modifications in estimates of future climate change (e.g., through the inclusion in models of the effects of aerosol cooling), the limits of uncertainty in possible global-average warming for a future doubling of $CO2$ have not been narrowed; that uncertainty has been in the 2.7–8.1°F (1.5– 4.5°C) range for the past 20 years for most GCMs.

While the capacities and speed of supercomputers have progressed dramatically in recent years, climate models remain constrained by current computational capacity. In fact, the leading climate models are no longer in the United States because U.S. researchers do not have access to the more powerful Japanese computers that other nations (i.e., Canada, Japan, United Kingdom) are using. Current computer capabilities applied to climate modeling are modest compared to what is needed to run high-resolution simulations using GCMs. Current computer limitations require that we settle for grid sizes that are much larger than needed to model some important phenomena such as tropical convection and precipitation.

The participants in the discussion agreed with the National Research Council's Report "Capacity of U.S. Climate Modeling (1998)" statement of the Council's "summary results", if not all the details of its Report.

Projections vs. Predictions

Thus, it was the consensus of the experts convened by the Annapolis Center that climate models may never be able to make greenhouse-warming PREDICTIONS with certainty because of the enormous number of variables involved and the uncertainty inherent in the future. On the other hand, models of greenhouse warming are essential in the learning process. Climate models can be used for making PROJECTIONS based on various assumptions that in turn may be useful in understanding the consequences of various human activities and policy alternatives. When such projections will represent possible real climate futures is difficult to judge because of the enormous scientific uncertainties involved.

CLIMATE PROJECTIONS are "what-if" scenarios about what might happen under a set of ASSUMED conditions. Projections may change as more knowledge is acquired. When weather forecasters make predictions one day or a week in advance, they can verify their predictions soon thereafter. Climate projections for the next century cannot be verified so easily. Continued climate warming year after year is not likely to occur. Periods of apparent cooling, however, would not necessarily mean that the Earth was not slowly warming over the long term.
Similarly, if we were to experience warming year after year, we should not assume that man-made climate change was the primary or only cause.

Conclusions

There are significant uncertainties in predicting future climates as a consequence of:

a. natural climate variability;
b. the potential for uncertain or unrecognized climatic forcing factors (e.g., explosive volcanism, new or unknown anthropogenic influences, etc.);
c. inadequate understanding of the climate system. We must expect that new observations or results from studies of global climate processes may yield information that causes us to re-evaluate and improve the capability of climate models. Our estimates of the credibility of climate system models can be, of necessity, consistent only with known facts and only based on the "best" current knowledge.