Global Climate Change: Predicting the Weather

In Greek mythology, Prometheus stole fire from the gods and gave it to humans. His action infuriated Zeus, who then chained the giant to a rock in the ocean where he was lashed by the seas and burned by the sun. Today, humans’ ability to capture energy and use it as we wish may be leading us toward a similar fate.

Records from glacial ice cores and direct air sampling confirm that since the industrial revolution, atmospheric concentrations of numerous greenhouse gases—those that allow sunlight energy in the earth’s atmosphere, but prevent heat from escaping—have increased substantially. Records also indicate that global mean temperatures have risen during this time, with a corresponding rise in sea level. Many climatologists believe that most of the increase in greenhouse gases is due to human activities such as deforestation and burning of fossil fuels. Their best estimate is that if we continue these activities at present rates, temperatures will continue to rise by about 0.3°C each decade.

Questions abound concerning climate change, such as whether increased concentrations of greenhouse gases definitely cause global warming or whether the warming is a normal climate variation; how the climate will change in the future, and what the impacts on human health, agricultural production, and natural ecosystems will be; and whether people have enough confidence in the predictions to justify legislating, or at least encouraging, changes in lifestyle such as building more energy-efficient homes or switching from coal-fired power plants to nuclear power.

Climate is the result of complex interactions of a vast number of processes. It is impossible to replicate climate in a laboratory and detailed historical records are limited. The difficulty of trying to forecast even local climate more than a few days in advance is summed up by the adage “it’s like trying to predict the weather.” Forecasting local weather presents a challenge to the best meteorologists, and trying to predict global climate over decades or centuries is a formidable task. By analyzing ice cores sampled from Greenland and Antarctica, scientists have been able to see how atmospheric levels of greenhouse gases differed in the past, and they can compare those differences to known variations in global temperature. But to predict how a build-up of greenhouse gases may affect climate in the future, scientists must rely on mathematical modeling.

Climate modeling has been conducted since the mid-1950s, when the rise of computer technology made mathematical simulation of such complex interactions possible. Since then, mathematical modeling has progressed from an obscure science to one of the most popular fields, of interest to scientists and academicians in dozens of other fields. Climate modeling achieved widespread exposure in the late 1980s when projections of global warming due to increased concentrations of greenhouse gases were made public. These projections seemed to be confirmed by the record-breaking heat waves of 1987 and 1988. Top scientists in the field were called to testify before the U.S. Congress. The dire predictions of a few experts, repeated and often amplified by the media, spawned demands for the government to take action.

In the past few years, the sense of urgency has slackened somewhat. Governments have hesitated to act, given the high short-term costs of reducing certain emissions and the uncertainties about the predictions. Some scientists and academicians have challenged the accuracy of the models and the way the projections have been interpreted. Others maintain that the models are accurate enough and that the price for delaying action could be disastrous. To begin to make reasoned judgments on whether to change behavior or what to expect if there is no change requires at least a rudimentary understanding of climate and climate modeling. “The only way to discuss the issue of climate change is to use the modeling approach,” says Suki Manabe, senior research scientist with the NOAA Geophysical Fluids Dynamics Laboratory at Princeton University. “The issue is far too complex to allow for theorizing or arm-waving. We’ve had enough of that already.”

Factors Affecting Climate

Global climate is determined by interactions among the atmosphere, ocean, cryosphere (snow and ice cover), biosphere, and geosphere. The driving energy behind the climate comes from the sun. Sunlight passes through the earth’s atmosphere and strikes the earth’s surface. Most solar radiation is absorbed by the earth’s surface, but about one-third is reflected from the surface in the form of infrared, or long-wave, radiation. Although some long-wave radiation is
lost into space, a portion is absorbed by gases in the atmosphere— principally water vapor, but also carbon dioxide, methane, chlorofluorocarbons, ozone, and other gases. The absorbed energy is reradiated in all directions, with the result that the earth's surface stays warmer (about 33°C) than it would without such gases. This phenomenon is known as the greenhouse effect.

Any factor that alters the radiation that is received from the sun or lost into space will affect climate. So, too, will any factor that alters the redistribution of energy within the atmosphere and between the atmosphere, land, and ocean. Increases in the concentration of the greenhouse gases reduce the efficiency with which the earth cools to space and tend to warm the lower atmosphere and surface—a process known as radiative forcing.

Based on sampling of ice cores in glaciers and direct air sampling done since 1958, atmospheric concentrations of certain gases, such as carbon dioxide, methane, chlorofluorocarbons, nitrous oxide, and tropospheric ozone, have been increasing over the past century.

Of these gases, carbon dioxide is of the most concern with respect to its role in climate change. The carbon dioxide component of the atmosphere has already increased 25% since preindustrial times (1750–1800) and is estimated to be growing at 0.5% per year. Climatologists estimate that the increase in atmospheric carbon dioxide has contributed about 60% of the climate change over the last two centuries. Man-made sources of carbon dioxide derive mainly from burning fossil fuels and deforestation, activities which are not likely to decrease in the near future unless government policies dictate otherwise. And because the level of atmospheric carbon dioxide adjusts very slowly to changes in source, the carbon dioxide emitted today will influence its atmospheric concentration for centuries. Thus, it is urgent to determine the effects of carbon dioxide.

Although greenhouse gases released at the earth's surface rise into the atmosphere, they do not equaliy stabilize there. Feedback processes come into effect as concentrations of gases increase. Carbon dioxide, for example, is continuously being absorbed by green plants and by chemical and biological processes in the oceans. The photosynthetic process of plants increases in the presence of higher atmospheric concentrations of carbon dioxide, and therefore could counteract some of the build-up by absorbing more carbon dioxide into the plants. Similarly, because the carbon dioxide content of the oceans' surface waters stays roughly in equilibrium with that of the atmosphere, oceanic uptake will slow the build-up to some extent.

Other feedback mechanisms, however, produce a positive effect. An increase in carbon dioxide induces an increase in water vapor, which would tend to amplify temperatures. A warmer earth would result in less snow and ice cover, which would result in a less reflective planet—one that absorbs more solar radiation.

Cloud cover is an extremely complex feedback mechanism; it can have either positive or negative feedbacks depending on such factors as density, composition, and altitude. Clouds at lower altitudes reflect more sunlight as temperatures increase and are thus assumed to have a negative effect on warming. Higher-altitude clouds, by virtue of absorbing reflected radiation from the earth, can have either a positive or negative effect based on their height and extent of cover. Because both cloud and snow/ice feedbacks are geographical in nature, these feedback mechanisms can only be addressed through the use of three-dimensional mathematical circulation models.

Modeling Global Climate

General circulation models (GCMs) are based on physical conservation laws that describe the redistribution of momentum, heat, and water vapor by atmospheric motions. All of these processes are formulated in equations, which describe the behavior of fluids (air or water) on a rotating body (the earth) under the influence of differential heating (the temperature difference from the equator to the poles) caused by the sun.

Variables predicted by the models typically include wind, temperature, humidity, rainfall, and surface pressure. To keep the task manageable, the calculations are done at discrete points on a three-dimensional grid of the earth. A typical horizontal grid size might be 2.8° latitude by 2.8° longitude—a distance of 290 by 290 kilometers. Vertical information might be expressed at as many as 15 different levels of varying height.

Unfortunately, many of the processes that affect climate occur on scales smaller than the model grid or time scale. Cloud formation, for example, occurs on a scale of a few miles or less. The effects of these small-scale processes have to be incorporated into the model by developing parameters, that relate factors such as average cloudiness within a grid cell to the average humidity and temperature.

“Parameterization is a compromise that leads to some errors in the result but, on average, should improve the accuracy of the models,” says Kevin Trenberth, author of Climate System Modeling and deputy director of the climate and global dynamics division of the National Center for Atmospheric Research.

The values of the predicted variables for each layer and grid point are determined in discrete time steps starting from some given initial conditions. To estimate the influence of greenhouse gases in changing climate, the model is first run for a few simulated decades with parameters set for present-day climate. If the parameters used in model equations appropriately represent atmospheric conditions, the statistical results will bear a close resemblance to the observed climate of the
atmosphere and ocean. The exercise is then repeated with an appropriately changed parameter—a doubling of carbon dioxide, for example—and the differences between this and the parallel control run are examined.

Early GCMs did not factor in the behavior of the oceans, which are a system of equal complexity to the atmosphere and a major determinant of climate. Recognizing the importance of the interaction between these two bodies, current GCMs now couple models of both the atmosphere and oceans. Not surprisingly, the time and expense to run such simulations with even the most advanced computers is enormous. "It can take several months to run a 50-year integration showing changes in the concentration of greenhouse gases," says Trenberth. "Since the beginning of global climate modeling, we've always counted on the next generation of computer to speed things up. But the demands for greater resolution and the desire to factor in new information on climatic processes always offsets the technological improvements in computing."

Model Interpretation
In 1988, the World Meteorological Association and the United Nations Environmental Program joined to form the Intergovernmental Panel on Climate Change (IPCC). The IPCC's goals are to assess available scientific information on climate change, assess environmental and socioeconomic impacts of climate change, and formulate response strategies. The IPCC published its first assessment of climate change in 1990, which was supplemented in 1992.

Citing the latest climate simulations with coupled atmospheric GCMs, the 1992 IPCC report states that globally averaged annual mean surface-air temperatures will increase between 1.3 and 2.3°C with an effective doubling of carbon dioxide in the atmosphere. The models variously assume a doubling will occur within 60–100 years at present rates of carbon dioxide emissions (the "business-as-usual" scenario).

Three of the five model outputs show relatively little warming during the first few decades, rather than a constant warming throughout. This reflects the thermal inertia of the oceans in responding to an increase in atmospheric temperature. All model results show the largest warming occurring in the high latitudes of the Northern Hemisphere, relatively uniform warming over the tropical oceans, and a minimum of warming or in some cases a cooling over the Northern Atlantic and the Southern Ocean around Antarctica.

Under the business-as-usual scenario for carbon dioxide emissions, the models project that global mean sea level will increase from 2 to 4 centimeters per decade, mainly due to thermal expansion of the oceans and the melting of some land ice. The IPCC's judgment is that global mean surface air temperature has already increased between 0.3 and 0.6°C over the last century. The report states that the size of this warming is "broadly consistent" with predictions of climate models based on known increases of carbon dioxide. However, it also states that this increase is of the same magnitude as natural climate variability and could thus be due entirely to that.

Uncertainties and Shortcomings
Following the publication of results of global climate modeling in the late 1980s (coupled, coincidentally, with some of the warmest years on record), the public began to take seriously the notion that human activities might be leading to global climate change. The media trumpeted the worst-case scenarios, often presenting projections as accepted fact. Congress held hearings at which some scientists predicted widespread disaster lest action be taken to reduce emissions of greenhouse gases.

Since then, there has been a certain amount of backpedaling on the part of both the public and the scientific community. Many scientists were quick to denounce the more extreme predictions of their peers. Misrepresentation of certain facts by the media had to be corrected or explained. As people became better educated about the complexities of modeling climate systems, many tempered their willingness to accept projections as probabilities.

Perhaps the most vocal critic of the popular models and projections is Richard Lindzen, Alfred P. Sloan professor of meteorology at MIT. In the 1993 issue of National Geographic Research and Exploration, Lindzen wrote:

Model predictions of large warming depend on projected large increases in atmospheric CO₂, and mechanisms within the models which act to greatly amplify the climate response to increasing CO₂. The projections depend on questionable economic, population, and energy scenarios; they also depend on clearly inadequate chemical models which serve to exaggerate the fraction of emitted CO₂ remaining in the atmosphere ... Under the circumstances, the possibility of large warming, while not disproven, is also without meaningful scientific basis.

Few climatologists share Lindzen's degree of skepticism, but all would say the models must continue to be refined and validated however possible.

The only way to validate global climate models is to assess their ability to predict past and present climates, given the data available. But even this is not a simple matter given the lack of comprehensive and readily usable data from around the globe.

When depicting the present climate, the models achieve mixed results. On the positive side, the IPCC report states that the models the panel analyzed exhibit "considerable skill in the portrayal of large-scale distribution of the pressure, temperature, wind, and precipitation in summer and winter." However, the report states that all models showed "significant errors" in reproducing these variables on regional scales. Validation for five selected regions showed errors in mean surface air temperature of 2–3°C. Average rainfall for those regions showed mean errors from 20 to 50%.

In all models, considerable uncertainties remain about the ability to portray such key factors as vertical mixing of heat in the oceans and formation of clouds. "We know clouds play an important role in climate, but we don't know how to model them well," says Trenberth. "Clouds cover the globe, yet they vary in nature on a micro-scale. Clouds with dif-
different [moisture] droplet size have different brightness and reflect different levels of radiation back into space. Learning how to model this is a major challenge."

It's only natural that people want to know how global climate change might affect their particular region. However, climate scientists such as Michael Glantz, head of the Environmental and Societal Impacts Group at the National Center for Atmospheric Research, are dismayed by the way some scientists are using the GCM's large-scale aggregations to project effects on such phenomena as future rice production in Thailand. "The GCMs are valuable for understanding how global climate works, but I have little confidence in their ability to project impacts on a regional scale," says Glantz. "The horizontal resolution in current GCMs is too coarse to tell you who the winners and losers are on a regional basis, yet people are trying to do just that. It's a gross misuse of the tool."

Future Directions

Despite, or because of, the shortcomings of past models, scientists are pushing ahead with new developments in modeling the response of global climate to increases in atmospheric greenhouse gases. The emphasis now is on running transient climate simulations with coupled global atmospheric-ocean GCMs as opposed to equilibrium studies using separate GCMs. Equilibrium studies assume that all other components of the climate have fully responded to the doubling of carbon dioxide in the atmosphere. In fact, scientists know that many processes, such as oceanic temperature, change very slowly in response to increased carbon dioxide or air temperature. A transient simulation that shows such changes over time should more closely simulate reality.

Progress is also being made in the simulation of regional climate change. Recognizing that simple interpolation of coarse-grid GCM data to a finer grid is inadequate, scientists are nesting regional climate models into the GCMs. These models include more detailed effects of topography, land-sea contrasts, and land-surface processes against which large-scale climate effects can be analyzed.

New attention is also being paid to the critical role of feedback processes in determining the climate's response to increased greenhouse gases. Discussions have gone back and forth as to whether atmospheric water vapor, the principal greenhouse gas, would increase or decrease with warmer temperatures. The consensus now seems to be that it would increase at most levels.

Cloud feedback remains a major area of uncertainty in models. Although the treatment of clouds in GCMs is becoming more complex, a clear understanding of the consequences of different cloud parameterizations has not yet emerged.

Improvements in model validation are also being made. A model's performance can be evaluated against available seasonal climatological distributions of the large-scale variables such as temperature and circulation. These evaluations have uncovered a number of common systematic errors in the parameterization of physical processes. For example, the simulated climate in most models was colder than that observed on average, and all models showed a cold bias in the middle and high-latitude upper troposphere and in the tropical lower stratosphere.

The availability of appropriate observational data is a critical factor in the validation and improvement of climate models, and some progress has been made in assembling global data sets for selected climate variables, such as average monthly surface air temperature and precipitation. For other variables such as cloudiness, precipitation, evaporation, water runoff, surface heat flux, surface stress, oceanic currents, and sea ice, however, the observational data remain inadequate for the purposes of model validation. These variables are relatively difficult to observe on a global basis and are not easily inferred from available statistics.

It may be that no amount of data can provide the ability to model certain key processes that drive climate. "Some aspects of the climate system may not be predictable because of the natural variability of the system," says Trenberth. "That doesn't mean the models can't be improved. It does mean they may not be able to do everything we'd like them to."

The question remains whether the models are accurate enough with respect to global warming to justify taking action. "There's no question that increased carbon dioxide emissions will lead to increased air temperatures," Trenberth says. "The question is, how much and how soon? The models indicate there will be significant warming in the not-too-distant future. I believe we should be taking some action—not drastic action—but at least creating incentives that encourage people to follow more environmentally benign lifestyles."

That has been the position of the National Science and Technology Council which helped craft President Clinton's Climate Change Action Plan, issued in October 1993. "We would not be taking the policy position of moving forward with prudent measures if we didn't have faith in the models," said Susan Tierney, policy vice chair of the Council's Global Change Subcommittee. "That said, we recognize there are uncertainties. Therefore, the actions proposed in the plan are in the form of voluntary partnerships with private industry rather than draconian measures such as heavy taxes."

As an illustration of the administration's viewpoint on global warming, Tierney points to a story cited in the preface to the Action Plan. A French general asks his gardener to plant a tree in the garden. "Oh, this tree grows slowly," the gardener responds. "It won't mature for a hundred years." "Then there's no time to lose," the general answered. "Plant it this afternoon."

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