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Climate Models: A Primer

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The Marshall Institute – Science for Better Public Policy

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Executive Summary

Concern about potential human impacts on the climate system has generated interest in predicting future climate and focused public attention on climate models—the tools used to make such predictions. Climate is the result of complex interactions among a number of factors: solar radiation, greenhouse gases, land cover, etc. The interactions between these factors are usually non-linear; in mathematical terms, climate is a chaotic system. This means that small changes in inputs (e.g. solar radiation) can have large and unpredictable effects on the system's output (e.g. temperature). However, chaotic systems can be predictable over a limited range of change. Based on our understanding of the climate of the last century, it is reasonable to assume that climate may be predictable for a few decades into the future, but unpredictable centuries into the future.

Climate models are a mathematical representation of the physical and chemical processes occurring in the climate system. Because our understanding of these processes is incomplete, current climate models do not accurately represent the climate system. Some climate models have been adjusted, or calibrated, to provide a reasonable simulation of some aspects of recent climate. However, calibrating a model to make its output look more like the real world does not provide a basis for assuming it will generate realistic predictions of future climate. Realistic predictions of future climate are assured only if the climate model is validated and run with an accurate set of inputs.

- A model is considered *validated* if it is developed using one set of data and its output is tested using another set of data. For example, if a climate model was developed using observations from 1901 to 1950, it could be validated by testing its predictions against observations from 1951 to 2000. At this time, no climate model has been validated.
- The inputs required by climate models include both natural variables (e.g. changes in solar radiation) and human variables (e.g. greenhouse gas and aerosol emission rates). Currently, neither set of inputs is predictable over the 100-year and longer periods of interest for climate model studies. While the prediction of future values for natural variables may be possible some day, the human variables, which depend on rates of population growth, economic development, and technological change, are probably unknowable.

Faced with the inability to predict future climate, climate modelers fall back to projecting climate scenarios. A climate scenario is the output of a climate model calculation and, by definition, is no better than the quality of the input data and model. The Intergovernmental Panel on Climate Change (IPCC) addressed this uncertainty by using a range of future emission rates and an array of climate models. The results show that using a single set of emission rates in the array of models produced as large a range in global average temperature in 2100 as using the range of emission rates in a single model. Clearly, caution is required when dealing with results as uncertain as these.

Introduction

Any discussion of climate models must begin with an understanding of:

1. The distinction between climate and weather, and
2. What scientific models are.

Weather is what we experience on a day-to-day or seasonal basis. Today's high temperature or the amount of snowfall in a winter are examples of weather. *Climate* is the long-term, typically thirty-year, average of weather. The average high temperature for this date or the average snowfall for a winter is an example of climate.

People have always realized that weather is changeable and unpredictable more than a few days in advance, but for much of human existence, the assumption was that climate, the average of weather, would remain relatively constant. Future winters would have the same total snowfall as this winter, and future summers would be similar to this summer.

We now know that climate changes on a continual basis, and a whole field of science, paleoclimatology, developed to study past changes. And for the first time, because of concerns about potential human impacts on the climate system, we are interested in predicting future climate. This interest in future climate focuses public attention on the tools used to make such predictions: climate models.

Scientific models, including climate models, are mathematical descriptions of the behavior of natural phenomena and systems, which allow scientists to study the relationships between the factors affecting these phenomena and systems. In this role they are indispensable tools for scientific research. The very best scientific models make accurate predictions of the behavior of the system, either in the future or if one or more input factor is changed. However, scientific models require validation before their output is trustworthy. A scientific model is validated by testing it against an independent set of data. For example, if a climate model was developed using observations from 1901 to 1950, it could be validated by showing that its predictions matched observations from 1951 to 2000.

Predictability in the Climate System

Climate is the result of a complex set of interactions between numerous factors, for example:

- the intensity of the solar radiation reaching the Earth;
- land-cover, which affects the amount of solar radiation reflected from the Earth's surface;
- energy and water vapor transport in the atmosphere and between the atmosphere and oceans;

- the amounts of greenhouse gases and aerosols in the atmosphere; and
- volcanic eruptions, which can affect both greenhouse gas and aerosol concentrations.

The interactions between these factors are usually non-linear, which means that a change in one factor will not result in an easily predicted change in climate. Overall, the climate system is highly non-linear. In mathematical terms it is a *chaotic* system, which means that small changes in the inputs to the climate system (e.g., solar energy) may have large and unpredictable effects on the system's outputs (e.g., temperature, precipitation).

> *[Climate] is a chaotic system, which means that small changes in the inputs to the climate system (e.g., solar energy) may have large and unpredictable effects on the system's outputs (e.g., temperature, precipitation).*

Chaotic systems can be predictable over limited ranges of change. For example, weather, which is also a chaotic system, can be predicted with reasonable accuracy for a few days, but is unpredictable for periods of two weeks or longer. Climate models attempt to predict average temperature, precipitation, and cloud cover decades or centuries in the future, but none would claim the ability to predict future weather, i.e., whether it will rain in Washington, DC on July 4, 2025. The limits of climate predictability currently are not known, but, based on the understanding of the climate of the last century, it is reasonable to assume that climate may be predictable for a few decades into the future, but unpredictable for centuries into the future.

There are two possible scientific approaches to predicting climate: extrapolation and models. Given the complexity of the climate system, extrapolation is clearly inadequate. Only models offer the potential for making predictions of future climate.

Scientific Models

The use of models to describe and predict the behavior of the climate system is normal scientific procedure. When scientists study a system, they usually try to model the way it operates or functions. They try to develop mathematical equations to describe the individual processes they observe, and then solve all of these equations simultaneously to see whether the mathematical results describe the overall behavior of the system.

Perhaps the best example of this modeling process is the astronomy of the solar system. The Sun and each of the planets exerts a gravitation field, which can be described mathematically. If all of the resulting equations are solved simultaneously—a laborious calculation by hand, but relatively easy with computers—it is possible to calculate where each planet will be at any time in the future. In this case, knowledge of the variables is precise enough to allow space probes to rendezvous with the outer planets years after the probes were launched.

When the results of modeling calculations do not describe the performance of the system correctly, it is an indicator that either the inputs to the model are incorrect or that the equations in the model do not correctly describe the processes in the system. Going back to the model of the solar system just described, it was the observation that the orbit of the planet Uranus did not behave as predicted by the model that led to the discovery of the planet Neptune. In this case the equations were right, but an input was missing.

Inputs to scientific models come from many sources. The best quality inputs are direct measurements, but these are often unavailable. If direct measurements are not available, the next best quality inputs are those derived statistically by extrapolating from measured values. Finally, if there is insufficient information to allow a statistical approach, inputs are guessed at using expert judgment. These are the poorest quality inputs, but are often needed to allow use of a scientific model. The confidence in a model's output is, in part, a function of the quality of the inputs it uses.

Climate Models

Modeling the climate system uses the same general approach as is used in the astronomy example cited above. The climate system obeys the fundamental laws of physics: e.g., mass and energy must be conserved. Many processes, such as the reflection of radiation from the Earth's surface and the warming effect of greenhouse gases, are known to occur. Climate models attempt to express all of these phenomena as a set of mathematical equations. However, because scientific understanding of many climate processes is incomplete, current climate models do not accurately represent the climate system.

Most climate model outputs do not closely simulate conditions observed in the real world. However, some climate models have been adjusted, or calibrated, so that they provide a reasonable simulation of some aspects of climate. Advocates use these simulations to claim that the models are valid representations of the climate system.

> *However, because scientific understanding of many climate processes is incomplete, current climate models do not accurately represent the climate system.*

The difference between *calibration* and *validation* of models is critical. Climate models are routinely calibrated, or adjusted, to make their output look more like the real world. However, calibrating a model to produce a realistic simulation of current climate conditions does not provide a basis for assuming that the model will generate realistic projections of future climate conditions. Realistic projections of future climate require a model that has been validated and uses an accurate set of inputs. Validation requires that the model be developed using one set of data and then its output shown to match an independent set of data. For example, if a climate model was developed using observations from 1901 to 1950, it could be validated by testing its predictions against observations from 1951 to 2000. At this time, no climate model meets these conditions.

How Climate Models Work

While climate models are relatively simple in concept, their use is horrendously complex for several reasons.

1. The climate system consists of two inter-connected sub-systems: the atmosphere and the oceans. While the importance of the atmosphere in the climate system is obvious, it is the oceans that contain the overwhelming share of the energy in the system. Change in the atmosphere can be rapid, but change in the oceans is slow. Any calculation of future climate must take this slow change in the oceans into account.

   The physical processes taking place in the atmosphere and the oceans are different. The most advanced climate models, called coupled atmosphere-ocean general circulation models (abbreviated AOGCMs, or just GCMs), attempt to model all the major climate processes in both the atmosphere and the oceans. Technically a GCM could refer to a climate model of just the atmosphere. However, in this paper, GCM will refer to a climate model that includes both the atmosphere and oceans.

2. Neither the atmosphere nor the oceans are homogeneous. To deal with the complexity of the real world, many climate models use a Cartesian grid approach, dividing both the atmosphere and oceans into a set of boxes or cells.[1] Simpler Cartesian grid climate models, such as the one developed by MIT's Joint Program on the Science and Policy of Global Change, use a two-dimensional approach, in which the cells for the atmosphere are latitudinal bands. However, the most complex climate models, such as those developed by NASA's Goddard Institute for Space Studies, or the UK Meteorological Office's Hadley Centre, use a three-dimensional approach, in which the atmosphere is divided into cells that are about 200 miles square and vary in height from a few thousand feet close to the surface to several miles at the top of the troposphere. The oceans are also divided into cells, though the size of ocean cells need not be the same as the size of atmospheric cells. Three-dimensional GCMs are considered the most advanced available climate models. The remainder of this paper will focus on their capabilities and shortcomings.

   Conditions within a single cell are assumed uniform, but practical experience indicates that both the weather and climate can be very different over a distance of 200 miles, particularly in mountainous or coastal regions. Computer simulations have shown that for areas with highly diverse climate, such as Britain, it is necessary to reduce cell size by a factor of about 7, to about 30 miles on a side, to accurately simulate some aspects of climate.[2] Reducing the length and width of cells by a factor of 7 requires an increase in the computing requirement by a factor of almost 50, assuming that no reduction is made in the height of the cells. This is beyond the current capacity of even the best supercomputers.

3. Running a climate model also requires a set of initial conditions, i.e., the weather conditions around the globe at a specific time. As noted above, climate is a chaotic system, which means that small changes in initial conditions can result in large changes in output conditions. One of the ways of handling this problem is to run the model using an ensemble of varying initial conditions. Output results that are relatively independent of initial conditions are probably more robust and more believable than output results that are dependent on initial conditions. While climate modelers agree that using the ensemble approach is highly desirable, the practicalities of computer capacity and availability mean that it is rarely used.

4. The climate model is run, using standard numerical modeling techniques, by calculating the changes indicated by the model's equations over a short increment of time—20 minutes in the most advanced GCMs—for one cell, then using the output of that cell as inputs for its neighboring cells. The process is repeated until the change in each cell around the globe has been calculated. In a perfect model, results for the initial cell at the end of the calculation would be the same as those determined at the start of the calculation. However, climate models are far from perfect, requiring the whole process to be repeated and smoothed, again using standard numerical calculation techniques. Eventually, a consistent set of results is determined for the first time step. The whole process is repeated for the next time step until the model is run for the desired amount of time.

   All of this takes huge amounts of computer capacity; running a full-scale GCM for a 100-year projection of future climate requires many months of time on the most advanced supercomputer. As a result, very few full-scale GCM projections are made. Modelers have developed a variety of short cut techniques to allow them to generate more results. Since the accuracy of full GCM runs is unknown, it is not possible to estimate what impact the use of these short cuts has on the quality of model outputs.[3]

Shortcomings of Climate Models

Climate modelers are the first to state that their models cannot predict future climate. The U.S. Climate Change Science Program (CCSP) defines *prediction* as:

> A probabilistic description or forecast of a future climate outcome based on observations of past and current climate conditions and quantitative models of climate processes…[4]

Modelers prefer to say that their models provide projections of future climate. *Projection* is defined by the CCSP as:

> A description of the response of the climate system to an assumed level of future radiative forcing. … Climate 'projections' are distinguished from climate 'predictions' in order to emphasize that climate projections depend on scenarios of future socioeconomic, technological, and policy development that may or may not be realized.[5]

Put another way, a projection is the output of a model calculation and is only as good as the model's equations and inputs. While climate modelers are careful to make the distinction between prediction and projection, the media and political processes rarely do; they treat most model outputs as predictions.

… there still is no agreement among climate scientists about the physics of some key climate processes, such as cloud formation. The quality of climate models cannot improve until these key climate processes are better understood.

Climate scientists generally agree on the shortcomings of current climate models and their projections. Many lists of these shortcomings exist; the following is taken from the IPCC Third Assessment Report. The term "forcing" used several times in this list means a factor that can drive climate change.

- Discrepancies between the vertical profile of temperature change in the troposphere seen in observations and those predicted models.
- Large uncertainties in estimates of internal climate variability (also referred to as natural climate variability) from models and observations.
- Considerable uncertainty in the reconstructions of solar and volcanic forcing which are based on limited observational data for all but the last two decades.
- Large uncertainties in anthropogenic forcings associated with the effects of aerosols.
- Large differences in the response of different models to the same forcing.[6]

Others typically add uncertainties about the roles of clouds and ocean currents in the climate system, and the sensitivity of the climate system to changes in greenhouse gas concentrations, to the IPCC's list.

Media Misrepresentations of Climate Model Results

IPCC's projection of global average temperature rise to 2100 was one of the Third Assessment Report's most widely quoted results. IPCC said:

> The globally averaged surface temperature is *projected* (*italics* added) to increase by 1.4 to 5.8°C (2.5 to 10.4°F) over the period 1990 to 2100. These results are for the full range of 35 SRES scenarios, based on a number of climate models.

Media reports typically focused on the upper end of this range, did not explain that it was based on climate model projections, or explain the difference between a projection and a prediction.

USA Today (October 26, 2000) reported:

> By 2100, global warming could raise the average temperature of the Earth as much as 10 degrees [Fahrenheit] more than the average temperature in 1990, according to a U.N.-sponsored panel of hundreds of scientists.

The Independent (London) (January 22, 2001) was even more certain. Its headline read: "World Will Be 6C Warmer by 2100, Scientists Forecast."

The body of the article stated:

> Scientists on the Intergovernmental Panel on Climate Change (IPCC), the official United Nations body assessing global warming, are likely to predict that the average temperature rise across the world by the year 2100 may be up to 6 degrees Celsius, or 11 degrees Fahrenheit.

The last point on the IPCC's list, large differences in the response of different models to the same forcing, is perhaps the most indicative of the limitations of current climate models. These differences occur because different climate models use very different mathematical representations of the same climate processes. They do this because there still is no agreement among climate scientists about the physics of some key climate processes, such as cloud formation. The quality of climate models cannot improve until these key climate processes are better understood.

Despite this scientific agreement on the shortcomings of climate models, the ways in which they are portrayed to the public vary greatly. The IPCC, which depends on climate model results for many of its assessments, cites the advances in model capability, in particular, the ability of some models to simulate the global average surface temperature record of the last 140 years, as reasons for confidence in their outputs.[7] However, as was pointed out above, calibrating, or adjusting, a model to produce a realistic simulation of some aspect of current climate does not provide an adequate basis for assuming that the model will provide realistic projections of future climate. Realistic projections of future climate require a validated model using an accurate set of inputs. A model can be considered validated only if its outputs replicate an independent set of data to replicate past climate. At this time, no climate model has been validated.

A more realistic assessment of the state of climate models was provided by the National Academies of Sciences (NAS), which concluded in its evaluation of the IPCC:

> … climate models are imperfect. Their simulation skill is limited by uncertainties in formulation, the limited size of their calculations, and the difficulties in interpreting their answers that exhibit almost as much complexity as nature.[8]

While it may eventually be possible to validate a climate model, providing the accurate inputs that a model would need to predict climate many decades into the future is a challenge of enormous proportions, and, in fact, may be an insurmountable problem. Evaluating potential future human impacts on the climate system requires accurate input about future human emissions of greenhouse gases and aerosols, as well as information about future land use patterns. These, in turn, will be determined by patterns of economic development, which are unknowable decades into the future. The CCSP summed up these concerns as follows:

… providing the accurate inputs that a model would need to predict climate many decades into the future is a challenge of enormous proportions, and, in fact, may be an insurmountable problem.

> Future human contributions to climate forcing and potential environmental changes will depend on the rates and levels of population change, economic growth, development and diffusion of technologies, and other dynamics in human systems. These developments are unpredictable over the long timescales relevant for climate change research.[9]

In addition to these concerns about potential human impacts on the climate system, a number of important scientific variables, such as changes in the intensity of the solar radiation, are currently poorly understood, and may be unknowable. For example, while there is an active scientific debate over the mechanisms by which changes in the intensity of solar radiation reaching the Earth translate into changes in climate, there is no debate over three facts:

1. Solar radiation is the source of energy in the climate system;
2. Changes in the intensity of solar radiation will affect global climate; and
3. We currently do not know how to forecast future changes in solar intensity.

Until it is possible to forecast future changes in solar intensity, volcanic eruptions, and other natural parameters in the climate system, accurate predictions of future climate are not possible.

Climate Scenarios

Faced with the inability to predict future climate, climate modelers fall back to projecting climate scenarios. The CCSP defines a climate scenario as:

> A plausible and often simplified representation of future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change.[10]

Just because a set of climatological relationships is consistent does not mean that those relationships are correct. The same tests of plausibility used for all other scientific findings should apply to climate scenarios.

Currently, the most widely used set of climate scenarios are the SRES (Special Report on Emission Scenarios) scenarios published by the IPCC in 2000.[11] Development of the SRES scenarios was a two step process.

First, the IPCC developed four "storylines," i.e., visions of the world's economic development to 2100. These storylines varied in the degree to which economic development was globalized, whether population peaked at about 2050 or continued to grow through 2100, and the degree to which environmental concerns other than climate change affected technological development and economic growth. These story lines were then used by six modeling teams to generate some 35 baselines scenarios, i.e., scenarios which assume that no explicit actions will be taken to during the next 100 years to limit greenhouse gas emissions. Other than this one point of consistency, the SRES scenarios cover a wide range of possible economic and environmental futures, from a world that uses little fossil fuel to a world that uses many times current levels of fossil fuel consumption. Many of the SRES scenarios include reductions from currently projected rates of growth of greenhouse gas and aerosol emissions as the result of actions taken to meet other policy objectives, such as the control of local air pollution.

The IPCC is unwilling to assign probabilities to the likelihood of occurrence of any of the SRES scenarios, saying only that all are equally likely or unlikely to occur. However, to make the task of using these scenarios more manageable, the IPCC identified six "marker" scenarios as representative of the larger set. The IPCC suggestion that all six of the marker scenarios be used in any study based on the SRES scenario is largely ignored.

As a result of the way in which the IPCC scenario-building exercise was carried out, the SRES scenarios encompass a wide range of greenhouse gas and aerosol emission rates. For the purpose of this discussion, only the most important two—carbon dioxide and sulfates—are considered here. Because CO_2 is long-lived in the atmosphere (a century or more), cumulative CO_2 emissions are more important than emissions for any given year. Cumulative CO_2 emissions between 1990 and 2100 in the SRES scenarios vary from 794 billion to 2498 billion metric tonnes carbon, a range of more than three. Sulfate aerosols are short-lived in the atmosphere (a few weeks), so it is their annual emissions that are important. Annual sulfate emissions in 2100 in the SRES scenarios vary from 11 million to 93 million metric tonnes sulfur, a range of more than eight.

While baseline scenarios may have validity as a scientific exercise, they do not represent a likely future. Concern about potential human impacts on the climate system is already spurring efforts to reduce greenhouse gas emissions, mandated in the EU and voluntarily in the U.S. Whatever the future of the Kyoto Protocol, it is likely that these efforts will continue and grow. They will spur the development of new technology, and it is highly likely that this new technology will diffuse to the developing world, leading to a more global reduction in the rate of growth of greenhouse gas emissions.

Even as a scientific exercise, the SRES scenarios have been widely criticized as being unrealistic. Ausubel[12] points out that the higher emissions SRES scenarios are unrealistic given historical trends in decarbonization, i.e., the use of fuels with lower carbon contents. Ian Castles, former head of the Australian Bureau of Statistics, and David Henderson, Westminster Business School, London[13] in a series of letters to Dr. R. Pachauri, Chair of the IPCC, and in presentations at IPCC expert meetings, note a number of problems in the treatment of economic growth in the SRES scenarios. These include:

- Use of market exchange rates rather than purchasing power parity in evaluating national incomes;
- Results that indicate that average incomes in Asia could grow as much as 140 times during the 21st century, rates of growth that are far greater than ever experienced, even by the fastest growing economies; and
- Rates of growth in developing world emissions and/or income from 1990 to 2000 which were much larger than actually experienced.

Despite these criticisms, the IPCC recently announced[14] that it intends to use the SRES scenarios in its Fourth Assessment Report, due for publication in 2007. The Fourth Assessment Report also will include assessments of other scenario literature, including literature that is critical of the SRES scenarios.

The large differences between the results obtained using the same inputs and different models are an indication of how poorly the physics of the climate system are understood.

The second step in the IPCC's development of climate scenarios was to use the SRES emission scenarios as input to climate models. Because of the huge amount of supercomputer time required to run the actual models, this exercise was conducted using a simple model tuned to mimic the behavior of seven different GCMs.[15] Each emission scenario—model calibration combination produced an estimate of temperature rise to 2100. The IPCC then took the highest and lowest of these estimates as the boundaries for its estimate of temperature rise to 2100, i.e., the temperature range of 1.4 to 5.8°C. This was one of the major conclusions of the Third Assessment Report.[16]

In evaluating the results of this climate scenario exercise, the IPCC noted:

> By 2100, the range in surface temperature response across the group of climate models run with a given scenario is comparable to the range obtained with a single model run with the different SRES scenarios.[17]

In other words, using a single emissions scenario in the seven climate models that the IPCC chose gave as large a range in estimates of global average surface temperature in 2100 as the range in temperature estimates using a single model and cumulative emissions of CO_2 that varied by a factor of three and annual emissions of sulfate that varied by a factor of eight. The large differences between the results obtained using the same inputs and different models are an indication of how poorly the physics of the climate system are understood.

Clearly, caution is required when dealing with results that are as uncertain as these. However, those studying the potential impacts of climate change focus on the upper end of the IPCC's range of projected temperature change which, if the criticisms of the SRES scenarios have any validity, are the projections most likely to be wrong.

Improving Climate Models

Thus far, efforts to improve climate models focus on adding more and more functions with the objective of making them look more like the real world. The IPCC shows this trend in a figure titled "The Development of Climate Models, Past, Present and Future."[18] It shows climate models evolving from simple ones in the mid-1970s, which attempted only to describe the atmosphere, to the complex ones of the early 2000s, which attempt to describe the atmosphere, land surface, oceans, sea ice, sulfate and non-sulfate aerosols, the carbon cycle, dynamic changes in vegetation, and the effects of atmospheric chemistry. However, as Dr. Syukuro Manabe, who helped create for NOAA the first climate model that coupled the atmosphere and oceans, observed:

> Models that incorporate everything from dust to vegetation may look like the real world, but the error range associated with the addition of each new variable could result in nearly total uncertainty. This would certainly represent a paradox: The more complex the models, the less we know![19]

Consider the following example: If there is a validated model that depends on three input variables, each of which is known with 90 percent confidence, the output of that model should be viewed as having 73 percent confidence. However, if there is a validated model that depends on twenty inputs, each of which is known with 90 percent confidence, the output of that model will have only 12 percent confidence. The complex models envisioned by the IPCC have many more than twenty inputs, and many of those inputs will be known with much less than 90 percent confidence.

Also consider just one of the shortcoming of climate models cited by the IPCC (and listed earlier in this paper), their inability to reproduce the observed vertical temperature profile of the atmosphere. All climate models project that increased greenhouse gas concentrations should lead to the mid- and upper troposphere warming faster than the surface. However, data for the last two decades indicates that the troposphere has warmed at a considerably slower rate than the surface. In 2000, the National Research Council concluded that the differences in warming trends between the surface and troposphere were real, i.e., not the result of measurement errors, and that they were not adequately reflected in climate models.[20]

More recently, Chase, *et al.*,[21] researchers at the University of Colorado, Colorado State University, and University of Arizona, examined whether the differences between observations and the outputs of four widely-used GCMs were caused by either forcing uncertainties, i.e., uncertainty in the effects of greenhouse gases, aerosols, etc. on climate; or by chance model fluctuations, i.e., the variability caused by the model's representation of the chaotic behavior of the climate system. The authors found that neither of these factors explained the differences between model projections and observations. They further concluded:

> Significant errors in the simulation of globally averaged tropospheric temperature structure indicate likely errors in tropospheric water-vapor content and therefore total greenhouse-gas forcing, precipitable water, and convectively forced large-scale circulation. Such errors argue for extreme caution in applying simulation results to future climate-change assessment activities and to attributions studies and call into question the predictive ability of recent generation model simulations, the most rigorous test of any hypothesis.[22]

The errors identified are in the fundamental equations in climate models, and relate to the water vapor feedback that is part of every climate model. Without this feedback, doubling the atmospheric concentration of CO_2 would result in a global average surface temperature increase of 1.2°C. However, any increase in surface temperature will increase the rate at which water is evaporated and raise the average atmospheric concentration of water vapor. Since water vapor is a greenhouse gas, the result is a further increase in temperature. Climate models project that doubling the atmospheric concentration of CO_2 would result in a global average surface temperature increase of between 1.5 and 4.5°C. This large range is due to the differences in the way the models handle the water vapor feedback. The increase in atmospheric concentration of water vapor also results in models projecting an increase in global average precipitation.

Building more elaborate models at this time is unlikely to address the errors identified by the Chase, *et al.* As the Marshall Institute argued in it comments on the CCSP's Draft Strategic Plan: "... model development should proceed only as fast as theoretical understanding of the climate system and validation permit."[23] Water vapor feedback is understood in qualitative terms; greater quantitative understanding is now required.

On-going scientific studies offer hope that more quantitative understanding of the water vapor feedback is achievable. For example, a recent paper by Minschwaner and Dessler[24] discussed observations from NASA satellites and scientific analysis indicating that there is less water vapor in the upper atmosphere than assumed by some climate models. In other words, climate models overestimate the size of the water vapor feedback and therefore potential future temperature rise. These findings, if validated by additional studies and then incorporated into existing climate models, should reduce the spread between model outputs.

A better understanding of cloud formation and the role of clouds in the climate system also is needed, along with the role of intermediate-scale (10 – 50 mile) ocean currents in the transfer of energy in the oceans and between the oceans and atmosphere, and other climate phenomena. As better theoretical understanding is developed, models should be continually tested against observations and researchers ought to refrain from claiming victory when the models simulate one set of observations. Validation requires that a model simulate a wide variety of climate phenomena.

In addition to simulating the average surface temperature and the vertical distribution of temperature through the atmosphere, a valid climate model should also simulate the important cycles in the climate system, e.g., the El Nino/La Nina cycle and the North Atlantic Oscillation. To again quote Dr. Syukuro Manabe:

> The best we can do is see how global climate and the environment are changing, keep comparing that with predictions, adjust the models and gradually increase our confidence. Only that will distinguish our predictions from those of fortunetellers.[25]

An expert on analysis once observed that “all models are wrong but some are useful.” This may seem like a harsh indictment but it reflects a valuable insight. For complex systems, ones far less complex than the climate system, it is very difficult and perhaps impossible to write equations that accurately capture all of the processes that make up a system. And even if accurate equations can be written, there is the daunting challenge of obtaining data of consistent quality and accuracy. Some data come from comprehensive measurements, some from statistical estimates, and some from hypotheses. Under such circumstances, the best that models can do is produce estimates bounded by some level of uncertainty. Models that are validated and that use good data produce narrower ranges of uncertainty. Those that are not validated and do not have access to reliable data produce larger ranges of uncertainty.

It is in this context that the usefulness of climate models should be judged. There is much that is not understood about the climate system and interaction of key variables within that system. There is also a lack of comprehensive measurement and observational data. This explains why the best climate models produce such wide range of estimates of possible temperature increases over the next century—estimates that vary by a factor of three.

With such great uncertainty, these models have limited value as policy tools. Their value is primarily as research tools to help is learn more about the climate system and to better focus research efforts. The important limitations of these models are too often overlooked by the media and some advocacy groups. They focus on specific and sensational outcomes without acknowledging the many assumptions that underlie them and the fact that there is not a sufficient knowledge base to project climate many decades into the future and, in doing so, they fail a basic objective of communication —to inform.

Endnotes

1. For a fuller description of the Cartesian grid approach and for a discussion of an alternate climate modeling approach based on a spectral approach, see Legates, D.R. (2000): “Climate Models and the National Assessment,” published by the George C. Marshall Institute and available on their website: *www.marshall.org/article.php?id=71*
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