Article 6.3.4.3 **Mathematical Models of Human-Induced Global Change**

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Summary

Complex mathematical models requiring major computing power to tease out their implications are currently the main theoretical tool used to understand and predict the response of the climate system to external forcing, such as that resulting from the current human perturbation to greenhouse gas concentrations in the atmosphere. These models developed quickly over the last half of the 20th century and are in use at several modeling centers around the world. They typically contain sub-models of the atmosphere, land, and ocean, and sometimes also the biosphere. They are used to simulate climate change by imposing an external forcing similar to what the real climate has experienced over the last century and is projected to experience in the coming one. Confidence in their predictions of the gross geographical distribution of temperature change is probably warranted. However, confidence in the overall magnitude of the simulated change is not, mainly due to the current inability to incorporate important climate feedbacks stemming from processes that cannot be explicitly resolved by the models, such as changes in cloudiness as climate warms. The models predict not only a temperature response to increasing greenhouse gas concentrations, but also an increase in the intensity of the global hydrologic cycle. Though there is reason to have some confidence in this global-scale prediction, the simulated regional-scale changes in the hydrologic cycle are almost certainly not trustworthy. Increasing confidence in model predictions in these critical areas will involve improving the dialogue between model and observations, as well as wise investment of additional computational resources.

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Glossary

•*Anthropogenic*. Generated by human activity.

•*Climate sensitivity*. The global-mean equilibrium temperature increase that occurs for a given radiative forcing. It is often expressed as the global-mean warming that results from doubling of CO_2.

•*ENSO*. Acronym for El Niño—Southern Oscillation. It refers to the quasi-periodic cycle of warm and cold temperatures generated internally by the climate system in the tropical Pacific. The typical length of the cycle is 3-5 years.

•*Greenhouse effect*. The discrepancy between the earth's warm surface temperature and its relatively cold effective emission temperature as viewed from space due to the presence of greenhouse gases. If the earth's overall temperature is not changing, the sunshine it absorbs must be balanced by the infrared radiation it emits, thereby fixing its effective emission temperature. Because the atmosphere contains greenhouse gases, it absorbs much of the infrared radiation emitted by the surface. This places the effective source of the outgoing infrared radiation needed to balance the incoming sunshine a few kilometers above the surface. Since atmospheric dynamics require temperatures in the lower atmosphere to decrease with altitude, the surface must be warmer than the planet's effective emission temperature.

•*Greenhouse gas*. Any gas that absorbs radiation at wavelengths emitted by the earth and its atmosphere.

•*Hadley Cell*. The large-scale atmospheric convection cell that predominates in tropical and subtropical regions. It is characterized by rising motion the equator, divergence of air away from the equator aloft, sinking motion in the subtropics, and return flow from the subtropics back to the equator near the surface.

•*Radiative forcing*. This concept provides a means of quantifying external forcing, and is defined as the change in radiative flux at the tropopause due to a forcing agent. The radiative forcing due to a doubling of CO_2 is about 4 W/m^2.

•*Relative humidity*. The ratio, usually expressed in percent, of the concentration of water vapor in the atmosphere to the saturation concentration of water vapor. Relative humidity provides a measure of the amount of water vapor in the atmosphere relative to the atmosphere's capacity to hold water vapor.

•*Sulfate aerosols*. The particles generated by the burning of sulfur impurities in fossil fuels. These particles reflect sunshine and therefore could affect climate.

Body

1. Introduction

Concern about human influence on climate stems principally from the fact that greenhouse gas concentrations have been increasing in the atmosphere due to human activity for the past two centuries, thereby enhancing the planet's natural greenhouse effect. Since the early 1800's, carbon dioxide (CO_2) concentrations in the atmosphere have increased from 275 to 370 ppm (2002). Mostly attributable to the burning of fossil fuel to power machinery and generate electricity, some of the CO_2 increase is also due to deforestation, which releases carbon stored in the biosphere into the atmosphere. Though the increase in CO_2 comprises the bulk of the current anthropogenic radiative forcing, other greenhouse gases have also increased due to human activity since the beginning of the industrial era, most notably methane (from 750 ppb in 1800 to over 1750 ppb in 2002).

Even those lacking an expertise in climate science can readily see why it is not trivial to predict quantitatively the climate system's temperature response to this external forcing. First, such a prediction requires a detailed understanding of the complicated interactions between solar and terrestrial radiation and certain elements of the climate system. These elements include not only greenhouse gases, but also clouds, snow, sea ice, and vegetation. Second, it requires an understanding of how these elements are distributed. To illustrate how challenging this can be, consider the ubiquitous greenhouse gas water vapor. The distribution of water vapor is impossible to predict reliably without considering the atmosphere's circulation and temperature. To the extent that the atmospheric circulation and temperature change as the climate changes due to a greenhouse gas increase, the water vapor distribution will also change, further altering the greenhouse trapping of the atmosphere and the hence the climate itself. Unraveling the controls on the distribution of clouds, snow, sea ice, and vegetation and their response and feedback to climate change is at least as difficult a task. Third, predicting the magnitude and geographical distribution of the temperature response to an external forcing requires an understanding of the myriad ways in which heat is exchanged and transported within the atmosphere, ocean, and land. For example, the surface temperature at any given location is determined not only by radiative processes, but also by convective transport of heat to higher altitudes, horizontal heat transport through air currents, and latent and sensible heat flux exchange between the lowest portion of the atmosphere and the underlying surface. Moreover, it is clearly desirable to predict not only the temperature response of the climate to an increase in greenhouse gases, but also the alterations in the hydrologic cycle and the biosphere associated with climate change. Achieving these goals requires an understanding of the controls on the geographical distribution of precipitation, evaporation, soil moisture, and ocean circulation.

Since the earth system is so complicated, attempts to understand how its components will respond to external forcing generally require a theoretical approach that is commensurate in complexity. Scientists therefore rely heavily on complex mathematical models for the theoretical component of global change research. These models typically represent many processes on a multi-dimensional grid and so require significant computational power to tease out their predictions. Climate observation is of course also critical and is intimately connected with the development of the mathematical models. As with any scientific enterprise, observation is used to compare the predictions of the models against the behavior of the real climate.

2. Historical Development

Because anthropogenic climate change arises from the interaction between radiation and human-induced changes in concentrations of atmospheric constituents, the story of the modeling of global change begins with efforts to understand this process. Then it expands to include efforts to model other processes, first also in the atmosphere, then in the ocean, the land surface, and the biosphere as their relevance of these processes to the climate change problem became clear.

2.1 Early models

Though he relied on pencil and paper for his calculations rather than a computer, the renowned Swedish physical chemist Svante Arrhenius was the first to use the language of mathematics to make a quantitative estimate of the climate's sensitivity to an increase in greenhouse gases. The paper describing the calculation, published in 1896, was an attempt to explain the transition from the cold ice-age climate of 10,000 years ago to the much warmer climate of the late 19th century, the only global-scale climate variation known at that time. Arrhenius claimed that an increase in CO_2 could have caused such a warming. Though initially focused on explaining past climate change, Arrhenius quickly realized that the burning of fossil fuels, by that time widespread in the industrialized world, could lead to an increase in carbon dioxide in the atmosphere and a change in climate. In 1904, he wrote, "the slight percentage of carbonic acid [the term used at that time for CO_2] in the atmosphere may, by the advances of industry, be changed to a noticeable degree in the course of a few centuries." In hindsight, Arrhenius' words seem prophetic, though perhaps overly cautious, as the anthropogenic increase in CO_2 became apparent much more quickly than he anticipated.

Arrhenius' model treated the atmosphere as a single slab of material absorbing infrared radiation. As the opacity of this slab to infrared radiation changed due to variations in CO_2, the radiative flux to the surface was altered, resulting in surface temperature changes to maintain radiative equilibrium. This was also the basic theoretical framework underpinning later pioneering modeling studies of climate sensitivity throughout the first two-thirds of the twentieth century by G. Callander, G. Plass, and L. Kaplan. The main advance in these later models was incorporation of an improved understanding of the interaction between CO_2 and infrared radiation. Then, in 1963, F. Möller developed a model that explicitly included the interaction between radiation and atmospheric constituents at multiple levels of the atmosphere, rather than treating the atmosphere as a single slab, as Arrhenius had done. The temperature throughout the atmosphere was calculated by assuming radiative equilibrium at each level. In spite of its enhanced vertical resolution, Möller's model lacked realism in two significant ways: First, it was not able to predict the correct vertical temperature structure of the atmosphere, giving an unrealistically warm surface temperature and a much too steep decrease of temperature with altitude. And second, it gave improbably large surface temperature changes on the order of several degrees C for a doubling of CO_2 concentration.

The lack of realism of Möller's model led to major advances in thinking about climate, because it so clearly revealed the flaws in Arrhenius' and others' assumption of pure radiative equilibrium. The gross vertical temperature structure of the atmosphere is not determined only by the interaction of radiation with atmospheric constituents, but also by vertical transport of heat through convection. Convection occurs in the atmosphere when the surface air is lighter than the air above it, taking into account the expansion of air parcels as they rise to higher altitudes and lower pressures. This is precisely the situation in Möller's model: the warm surface air and the steep decrease in temperature with altitude means that the surface air is very light and buoyant relative to the air aloft. To restore gravitational stability, convective overturning would take place, warming the atmosphere aloft and cooling the surface. Taking Möller's model but applying the additional constraint that the atmosphere transports heat vertically to remove gravitational instability, S Manabe and collaborators developed the radiative-convective model. This model has a much more realistic surface and atmospheric temperatures, and a more plausible sensitivity of about a 1°C surface temperature increase to a doubling of CO_2.

In the late 1960s, Manabe and R Wetherald also began to use the radiative-convective model to explore quantitatively whether climate feedbacks might play a role in altering the climate's sensitivity to an external forcing. In the early 20th century others, including T Chamberlin and Arrhenius himself, had identified a process associated with water vapor as probably the most important climate feedback. They argued that an increase in CO_2 would lead to warming, which in turn would lead to an increase in water vapor in the atmosphere, since warmer air can hold more water vapor without becoming saturated. Since water vapor is itself a greenhouse gas, this would enhance the initial warming, leading to still more water vapor in the atmosphere. Manabe and Wetherald attempted to include this water vapor feedback in the radiative-convective model by assuming that the ratio of the water vapor concentration at each level to the saturation concentration of water vapor (i.e. the relative humidity), is a conserved quantity. They found that inclusion of water vapor feedback in this manner approximately doubled the climate sensitivity, so that a 2°C surface temperature increase occurred in response to a doubling of CO_2.

2.2 Development of GCMs

In parallel with these attempts to model global climate sensitivity with simple one-dimensional models, efforts were made to create mathematical models to predict weather. In the early 1920s by L Richardson grasped the possibility of explicitly solving the equations of fluid motion on a rotating sphere, and so simulating the large-scale movement of air masses and weather systems. However, the problem was intractable, mainly because it required seemingly overwhelming computational power. (Tongue in cheek, Richardson advocated employing tens of thousands of people to carry out the huge numbers of calculations required even for a single weather forecast.) The development of the computer in the 1940s suddenly made Richardson's plan seem less eccentric. By the mid 1950s, weather forecasting using numerical models run on primitive digital computers became routine. Constrained by limited computational resources and used exclusively for weather prediction, these early models made regional rather than global simulations. However, it was soon realized that the same numerical techniques, when extended to the entire globe, could be used to simulate the general circulation of the atmosphere. Such general circulation models---or GCMs---were constructed in the 1960s by Manabe and J Smagorinsky at the Geophysical Fluid Dynamics Laboratory (Princeton NJ USA), A Arakawa and Y Mintz at UCLA, and A Kasahara and W Washington at the National Center for Atmospheric Research in Boulder CO USA. The development of these global models was also facilitated by exponential increases in the speed and performance of digital computers, a trend that continues today. In fact, it is impossible to separate the development of mathematical models of global change from the development of the digital computer. Without the improvements in computing, the advances in mathematical tools to understand global change would have been unimaginable.

Armed with more computational resources and powerful GCMs derived from weather prediction models, scientists were able to focus on fundamental unsolved problems of the atmospheric circulation, including questions relating to climate, such as how heat, moisture and clouds are distributed and transported within the atmosphere. In the early 1970s Manabe realized that the representations of these processes made the GCM a valuable tool to study their role in climate change. Moreover, the GCM provided a three-dimensional global simulation of the climate's response to an external forcing. This would be a significant advance over the radiative-convective model, which collapsed the entire atmosphere into a single vertical column. In 1975, he and Wetherald published the results of the first CO_2 doubling experiment done with a GCM. The results were similar to what was predicted from the radiative-convective model, except that more warming took place in mid to high latitudes. This was mainly due to decreased snow cover in the warmer climate, which reduced the reflectivity to solar radiation, or albedo, of the high-latitude areas. More sunshine was therefore absorbed which led to warmer temperatures and still greater reduction in snow cover. This study therefore pointed to surface albedo feedback as playing a significant role in determining the geographical distribution of climate response to external forcing.

2.3 Coupling the atmosphere to the ocean, land, and biosphere

At approximately the same time, Manabe and oceanographer K Bryan realized that climate simulation could be further improved by coupling a numerical model of the ocean to the atmospheric GCM. All previous climate change modeling experiments had calculated the climate system's equilibrium response to an external forcing. However, mainly because of the ocean's enormous heat capacity, the climate system cannot immediately equilibrate to the external forcing. Some model of the ocean circulation and heat uptake is therefore required to simulate this transient response. This coupling of atmospheric and ocean models was the first hint of a trend toward integrated earth system models, where components of the earth system exchange information to simulate phenomena impossible to reproduce when the individual components are isolated. By the early 1980s, the coupled ocean-atmosphere model had developed to the point where it became possible to use it to simulate transient climate change.

Throughout the 1980s and 1990s, independent efforts to develop coupled ocean-atmosphere models for the purposes of climate change simulation began to bear fruit. Particularly noteworthy are the models developed at the Max Planck Institute in Hamburg, Germany, the Goddard Institute for Space Studies in New York NY USA, the Canadian Climate Centre in Victoria BC Canada, the National Center for Atmospheric Research in Boulder CO USA, and the Hadley Centre for Climate Prediction in the UK. The models all solve the same equations of fluid motion on a rotating sphere in both the atmosphere and the ocean and have similar radiation schemes. Their most significant differences include how they represent: (1) sea ice formation and transport in the ocean, (2) the turbulent lowest level in the atmosphere known as the boundary layer, and (3) sub-grid scale processes such as atmospheric convection, cloud and precipitation formation, and oceanic mesoscale eddies. These model differences reflect differences of opinion within the climate modeling community about how best to represent important processes that cannot be explicitly resolved on the model's computational grid. Climate modelers also differ in how much mathematical complexity is appropriate to represent these processes given subjective assessments of their relative importance for climate problems. Since more complexity requires more computational power, which is limited, difficult choices must be made about how much complexity to devote to each process.

The 1990s also saw significant developments in the modeling of the land surface and biosphere. The land surface models underlying the original atmospheric GCMs were very simple, predicting soil moisture as a simple balance between precipitation, evaporation, and runoff, and land surface temperature with a simple surface energy balance among latent heat flux, sensible heat flux, and radiation. Though the early models identified surface albedo feedback as an important factor in determining the geographical distribution of climate change, as noted above, snow and its effect on surface albedo was also represented in the simplest possible manner. To develop hypotheses for how snow cover and vegetation might respond to and influence climate change, it is necessary to incorporate more complex models of the land surface. These models are being coupled to atmospheric GCMs, and typically include multiple soil levels to account for water seepage as well as heat conduction and storage within the land surface. If snow cover is predicted, the snow layer as well as snow melt and accumulation processes are represented with comparable complexity. The land surface models also include exchange of moisture with the atmosphere from both the land or snow surface and the vegetation itself. In addition, they allow the vegetation to interact with atmospheric radiation, as optical properties of vegetation vary during the plants' life cycles and among plant species. And finally, some models explicitly predict the growth and decay of land plants in response to simulated environmental conditions.

Representations of ocean biological processes are also being incorporated into ocean models. Since the biology of the ocean is very sensitive to the nutrient composition of seawater, this always involves representations of chemical reactions among nutrients as well as the utilization of these nutrients by marine organisms. Modeling of ocean chemistry has a special significance too because of the ocean's role as the eventual repository for the carbon being pumped into the atmosphere by fossil fuel burning.

3. Current Methodology

The development and use of sophisticated mathematical models to simulate global climate change over the past century is one of the great achievements of climate science. These models have become widespread and indispensable tools for scientists and policymakers alike as they confront the climate change issue. Because of their prominent role in scientific and political debate, it is worthwhile to provide an overview of how these models are used. The design of climate change experiments, the technical difficulties encountered in running them, the value and limitations of climate simulation, and model validation against the observed climate record are all important issues discussed below.

3.1 Design of climate change experiments.

A model's equilibrium sensitivity to a given external forcing is a useful benchmark of model performance. The classic method of making this measurement is a CO_2-doubling experiment, where CO_2 concentrations are increased instantaneously or gradually until they reach their doubled value, and the model is then allowed to equilibrate to the stronger greenhouse effect. The greenhouse effect is enhanced to nearly the same degree in all models due to the doubled CO_2, so the simulated external forcing is very similar in all models. This calculation therefore provides a convenient method of comparing model response to external forcing. Surprisingly, climate models in use today respond quite differently to a doubling of CO_2. Some predict a global-mean warming as low as 2°C, implying that the net effects of water vapor, surface albedo, and cloud feedbacks are relatively small. Others predict more powerful positive feedbacks and give a much larger sensitivity, up to 5°C. The main reason for the divergent predictions of equilibrium climate sensitivity is often ascribed to differing simulations of cloud feedback, though other processes such as surface albedo feedback may also play a role.

It is also useful to carry out simulations of past climate change that allow direct comparison with the instrumental global climate record, which extends back in time roughly 100 years. Such a simulation requires knowledge of the external forcing the real climate experienced over the course of the instrumental record. The forcing history due to the greenhouse gas increase is quite well known, and is straightforward to impose on a climate model. It is trickier to include other forcings, mainly because they are poorly constrained. The direct radiative forcing due to the anthropogenic increase in sulfate aerosol concentration is not difficult to quantify and is usually included by assuming that a certain amount of sunlight is reflected to space in regions where aerosol concentrations have historically been high. However, sulfate aerosols may also have a substantial impact on the radiative properties of clouds, but the magnitude of this indirect effect is unknown and is therefore not typically included. Other forcings are also usually left out, including those stemming from stratospheric ozone loss, tropospheric ozone increase, soot pollution, changes in mineral dust concentration, land use change, and solar variability. These forcings are all likely to be small compared to the greenhouse gas forcing, though more must be done to verify this.

Estimates of future external forcing are also imposed on climate models to predict future climate change. Typically these scenarios of greenhouse gas increases involve assumptions about population growth, economic development, and improvements in energy efficiency. Obviously these assumptions are subject to considerable uncertainty, compounding the uncertainty surrounding the sensitivity of the models themselves. This further complicates the interpretation of the modeling experiments designed to simulate future climate change.

3.2 Technical issues.

When evaluating the predictions of a climate model, it is useful to keep in mind the technical problems a model faces. One salient problem is the phenomenon known as climate drift. When an atmospheric or ocean model is run by itself, sea surface temperatures (SSTs) must be prescribed to provide a boundary condition for the model. The surface constraint is usually strong enough that the model cannot stray much from realistic temperatures in the atmosphere or ocean interior. However, this constraint is eliminated when the two components are coupled and exchange heat at the air-sea interface. A significant error in any one of the two components can sometimes amplify, resulting in climate drift. For example, suppose the ocean model, because its currents are slightly weaker than the real ocean's currents, transports less heat to high latitudes than in reality. Upon coupling to an atmospheric model, the high latitude SSTs would begin to cool, resulting in sea ice growth. The high latitude atmosphere would also begin to cool in response to the cooler SSTs, depositing more snow on the land surface. The greater extent of sea ice and snow cover would reflect more sunshine back to space, resulting in even more cooling in surface temperatures over both the land and ocean. The mean state of the model would slowly drift away from reality. Typically this climate drift occurs on time scales of years to centuries. All coupled ocean-atmosphere models exhibit climate drift to varying degrees for reasons that are sometimes difficult to diagnose. Every climate change simulation is therefore done with a model whose mean state does not perfectly match the real climate's.

The example of climate drift described above could have a significant and detrimental impact on the simulated response to external forcing. If the extent of sea ice and snow cover are unrealistically large, the model will have a larger surface albedo feedback than it would otherwise. This will increase the model's sensitivity to increases in greenhouse gases and exaggerate the climate change in mid to high latitudes. The climate modeler in this case would be faced with the task of determining whether our not this effect is significant enough to render the model's predictions useless. Even if the drift does not seriously distort the model's mean state, its effect on model sensitivity must still be assessed. Coupling with land surface or biosphere models may also introduce new sources of climate drift.

In the late 1990s, various modeling teams began to unveil coupled ocean-atmosphere models that drift significantly less than previous models over the course of several hundred years of model integration. The models developed at the Hadley Centre for Climate Prediction and the National Center for Atmospheric Research (NCAR) are particularly noteworthy in this respect. This gives some hope that the climate drift problem will become insignificant in the near future.

3.3 Model validation

Scientific understanding only results from a meaningful dialogue between models and observations. Observations need to be interpreted with the help of conceptual and mathematical models, and models must be in turn be validated by observations. Though it is essential to advancing the science of climate, fostering a rigorous dialogue between climate observations and coupled GCMs is especially painstaking and difficult for two main reasons. First, the complexity and interconnectedness of the processes in the GCM and their counterparts in the real world means assessment of model performance must take place at multiple levels of detail, from the behavior of a single process to the overall quality of the global-scale simulation. Second, research-quality observations of important climate variables are limited in the time and space domain, both in continuity and resolution.

Validation of coupled GCMs usually begins by comparing the behavior of each major model component to available observations. This often occurs in parallel with model development. For example, during the construction of the radiation subroutine, the amount of infrared radiation absorbed by water vapor in the model might be compared with measurements of water vapor emissivity. Depending on its outcome, this process might result in an adjustment in the way the radiation subroutine handles this process. It is generally straightforward to carry out this preliminary validation if the relevant observations are available. Unfortunately this is not always the case. For example, the radiative properties of clouds are poorly constrained, thus allowing for a wide range of values to be assumed in the model without contradicting the observations.

Once the GCM has been constructed and its components validated to the extent possible, work may begin to validate the myriad phenomena that emerge from the simulated interaction of the components. Even if we had perfect knowledge of the real climate's unperturbed state, it would be too time-consuming to validate all these phenomena. Scientists overseeing a climate change experiment must choose the aspects of the simulation to compare most rigorously to the observations. In general the most emphasis is placed on those aspects of the model that define its present-day climate and influence climate feedbacks. These include the seasonal and geographical distribution of temperature, precipitation, snow cover, humidity, and cloud in the atmosphere and over land, and temperature, salinity, and sea ice extent in the ocean. Again, lack of observations makes this comparison imperfect. The observational record is particularly deficient in the high latitudes of the southern hemisphere.

Often a newly-constructed GCM will differ significantly from the real climate in its simulation of important climatic variables. The model must somehow be adjusted to improve the quality of the simulation. Usually this is accomplished by a procedure referred to as tuning. As noted above, observations of some quantities needed by model components are poorly constrained, allowing considerable leeway in values assumed in the simulation. It is often possible to improve the simulation's quality by adjusting these values. So long as the climate modeler does not stray outside the constraints imposed by observations in adjusting these values, the components of the "tuned" model do not contain more *ad hoc* assumptions than the unadjusted model, as is sometimes claimed.

Once the unforced model is validated and tuned as necessary, the next step is to validate its response to an external forcing. Limited long-term climate observations make this final step particularly unsatisfactory. One approach is to compare the model's response to the best guess of the external forcing over the past century against the twentieth century climate record. In principle this approach seems promising, especially as knowledge of the past forcings improves, as will undoubtedly occur. However, in practice it is not particularly helpful in distinguishing among models of widely varying sensitivities. For example, climate models with equilibrium sensitivities of 2°C and 4°C to a doubling of CO_2 can both be made to match the temperature record of the 20th century within observational uncertainties when the best-guess forcing is applied. Another approach that has been used with limited success it to validate the response of the model to climate forcings of the distant past against the paleoclimate record. For example, the temperature response of the model to the ice sheets and lowered CO_2 levels of the last glacial maximum can be compared to the temperature record of that time. Unfortunately, the uncertainty that still surrounds these observed temperatures is still considerable enough that only weak statements can be made about model realism based on this type of comparison.

Because improving the agreement between GCMs and the real world is so complex and painstaking, confidence in the models' ability to predict future climate will develop only gradually: As observations of quantities relevant for model components improve, the parameterizations of these components will become more realistic. Hopefully, these new parameterizations, when incorporated into GCMs, will result in simulations that more closely resemble the mean state of the real climate. Another factor favoring a gradual increase in confidence in the models is the fact that the greenhouse gas forcing of the 21st century will likely be much larger than that of the 20th. The climate response will be correspondingly larger and will also be relatively well-observed through satellite and ground-based measurements. The combination of a larger signal and reduced observational uncertainties may make it easier to distinguish among models with the current wide range of sensitivities.

4. Strengths and weaknesses of climate models

Model validation has revealed both strengths and weaknesses of state-of-the-art atmospheric GCMs for the climate change problem.

4.1 Simulation of present-day climate

Climate models not subject to any external forcing are generally able to simulate the observed present-day geographical and seasonal distribution of temperature reasonably well (see figure 1). This indicates that the models can simulate the seasonal heating of the atmosphere and ocean by the sun, the storage of this heat in the atmosphere/ocean system, and the infrared radiative damping of the resulting temperature anomaly back to space. This, in turn, is a reflection of the advanced state of knowledge of the interaction between atmospheric and surface constituents and radiation over the entire electromagnetic spectrum. The fidelity with which the models simulate the seasonal cycle of temperature also indicates that the seasonal cycle of heat transport within the atmosphere and ocean is simulated reasonably well.

Since the large-scale (>1000 km) general circulation of the atmosphere is driven by large-scale temperature gradients through well-known dynamical relationships, the success the models enjoy in simulating the correct geographical and seasonal distribution of temperature ensures that they also do a reasonable job of simulating the large-scale general circulation and its seasonal variability. For example, the Hadley Cell in most GCMs is about as vigorous as the observed, and the simulated mid-latitude jet stream generally have approximately the observed strength and geographical location. GCMs also do well in simulating the turbulent meanders and eddies of the mid-latitude jet stream, which are responsible for storm activity in mid-latitudes. This is because the fluid dynamical instabilities that lead to this turbulence are well-understood and are incorporated in the models.

The models are less successful in simulating the real climate's hydrologic cycle. Precipitation is notoriously difficult to simulate accurately (see figure 2). Though most GCMs capture the most striking features of the observed rainfall patterns (e.g. the locations of the world's major deserts and tropical forests), they usually miss the mark on smaller scales. An instructive example is the simulation of the intertropical convergence zone (ITCZ), an area of rising motion and intense precipitation located in the deep tropics over the regions most heated by the sun. In many models, the ITCZ is centered in approximately the right location, but precipitation within it is weaker and is spread out over too large an area. Many other features of the observed precipitation field are also too diffuse, or are somewhat displaced relative to the observed fields.

The difficulty in simulating precipitation with as much precision as temperature relates to the fact that precipitation occurs where moist air rises, cools, and becomes saturated. The rising motion is then balanced by sinking motion elsewhere. This overturning motion occurs on a wide range of spatial scales both smaller and larger than the size of a typical model grid box. Overturning larger in spatial scale than a grid box can be resolved explicitly by the model. For example, the precipitation associated with mid-latitude storms stems from rising motion that covers a spatial scale of hundreds of kilometers. Most GCMs can resolve this motion and therefore do a reasonable job simulating the associated precipitation. However, overturning often occurs on spatial scales as small as a kilometer or two, particularly in the deep tropics. The model cannot resolve this sub-grid-scale process. Instead, it must assign a mean precipitation value for the whole grid based on the grid-scale atmospheric conditions. Models have some success with this technique because sub-grid-scale overturning cells tend to be clustered in regions of large-scale rising motion. So a model can predict with some accuracy the existence of sub-grid-scale overturning cells and their associated precipitation based on its simulation of the large-scale motion fields. However, the precipitation value the model assigns to that grid box can differ significantly from what the average precipitation over the grid box would be if the small-scale motions were resolved explicitly.

Other fields whose prediction depends a great deal on knowledge of small-scale circulation, such as clouds and their radiative properties, are similarly difficult to simulate accurately. Humidity, especially in the tropical mid to upper troposphere where it is very sensitive to the locations of rising and sinking air, may also be in this category.

When evaluating the ability of a GCM to simulate present-day climate, it is useful not only to compare its mean state to that of the real climate, but also the magnitude and geographical distribution of its unforced variability. For example, the origin of the observed 20th century warming trend is one of the most controversial subjects of the climate change debate. Some suggest the trend is internally-generated by the climate system. Climate models can be used to assess whether this hypothesis is reasonable, but only if they accurately simulate the unforced variability of the climate system.

In mid to high latitudes, the main source of unforced variability on all time scales are the eddies that result from the instability of the jet stream. The current generation of climate models generally perform well in simulating the statistics of these eddies, and therefore have about the right amount of variability in these regions. In low latitudes, on the other hand, the models' simulation of unforced climate variability is of varying quality. On the time scales of interest for the climate change problem (>1 year), the low-latitude climate variability is dominated by the ENSO phenomenon. ENSO is centered in the equatorial Pacific and arises from complicated and unstable interactions between the atmosphere and ocean. Most coupled ocean-atmosphere models are able to simulate a phenomenon resembling ENSO; however, in many models the amplitude of the ENSO-related variability is either too small or too large, or the geographical pattern of the ENSO-related variability does not match the observed. The reasons for these discrepancies are not clear; however, as the ENSO phenomenon becomes better understood, its simulation will hopefully improve significantly.

The current generation of coupled ocean-atmosphere models is incapable of generating a trend as large as the 20th century warming trend when left to simulate climate variability without any external forcing for hundreds of years. However, the models are able to generate anomalies as large as some of the interdecadal variability seen in the record, indicating that some of the observed record's hills and valleys are likely to be internally-generated. As the simulation of unforced variability improves, particularly with regard to ENSO, stronger conclusions about the origin of the observed climate anomalies, including the 20th century warming trend, should be possible.

4.2 Equilibrium response to external forcing

Given these strengths and weaknesses of the unforced model simulations, how much confidence is warranted in the equilibrium simulated response to external forcing? To answer this question, it is necessary to examine explicitly the climate feedbacks that influence the simulated equilibrium response: surface albedo, water vapor, and cloud feedbacks.

Most GCMs simulate a positive surface albedo feedback. This feedback results from the decrease of sea ice and snow cover in the warmer climate and the resulting decrease in the planet's reflectivity to sunshine. Because sea ice and snow are formed when temperatures fall below the freezing point, and given the models' success in simulating temperature and its seasonal variability, it is very likely that the model prediction of less sea ice and snow cover in a warmer climate is correct, at least qualitatively. Simulated surface albedo feedback is responsible for a key feature of the predicted geographical distribution of the temperature response to a CO_2 increase: the larger warming at high latitudes compared to the tropics.

Most GCMs also simulate positive water vapor feedback. This feedback is positive because water vapor increases in the warmer climate throughout the model atmosphere. The saturation water vapor concentration, or water vapor holding capacity of the atmosphere, increases with temperature. The simulated water vapor concentrations increase in the warmer climate accordingly, keeping relative humidity approximately constant in all regions of the atmosphere. This further enhances the planet's greenhouse effect and therefore further increases surface temperature. There is little reason to doubt the prediction of increasing water vapor in the boundary layer (lowest few kilometers of the atmosphere), where turbulent mixing would draw additional moisture from the surface into a warmer atmosphere, maintaining water vapor close to saturation. Since the humidity distribution in mid to high latitudes is largely controlled by the turbulent eddies of the jet stream, which are well-simulated by the models, the models' water vapor feedback in these regions is probably also robust. However, in the tropical mid to upper troposphere, where the humidity is controlled to a great extent by sub-grid-scale vertical motion, as noted above, the humidity change in a warmer climate may be more complicated than the models' prediction of relative humidity conservation. The real climate's water vapor feedback in the tropics could therefore be more or less positive than the models currently predict.

The third feedback, cloud feedback, occurs because clouds interact strongly with both solar and terrestrial radiation. If clouds increase, they trap more infrared radiation, warming the surface. On the other hand, they also reflect more solar radiation back to space, cooling the surface. If simulated cloudiness increases in a warmer climate, the balance between these two effects determines whether the cloud feedback is positive or negative. This balance is sensitive and depends on where in the model atmosphere cloudiness increases. In fact, of the models predicting an increase in cloudiness in a warmer climate, some predict positive cloud feedback, while others predict negative cloud feedback. Further complicating the picture is the fact that some models predict cloudiness will decrease in a warmer climate. Some of these models also predict positive cloud feedback, while other predict negative cloud feedback. The models fail to converge to the same prediction of the sign and magnitude of cloud feedback because most clouds are formed by sub-grid-scale motion, while the models are forced to predict cloud amount based on grid-scale conditions. Cloud amount and hence cloud feedback are therefore highly sensitive to the method used to predict sub-grid-scale cloud formation. Differing simulations of cloud feedback is a main reason why models differ in their simulations of the equilibrium climate response to a CO_2 doubling.

In all climate change experiments, the simulated climate changes not only because the temperature increases, but also because the hydrologic cycle intensifies. This intensification is characterized by an increase in global evaporation and precipitation rates. It occurs because the enhancement of the greenhouse effect due to the increase in CO_2 and water vapor results in a large increase in downward longwave radiation at the surface. This must be balanced by surface heat fluxes. It turns out that the increase in upward longwave radiation stemming from the temperature increase is not sufficient to balance the increase in downward longwave radiation. Increases in latent and sensible heat fluxes must make up the difference. The increase in latent heat flux implies an increase in global evaporation, which in turn results in an increase in global precipitation, since the atmosphere is incapable of storing water vapor on time scales longer than a month or two.

Though the mechanism for the global-scale hydrologic cycle intensification is relatively well understood, it is clearly of greater practical interest to know how and why the changes in the global hydrologic cycle manifest themselves locally. In general, the models predict that precipitation will increase more in the regions of large-scale convergence and rising motion, where precipitation already occurs, while the evaporation increase will occur everywhere. This will exaggerate the current contrast between deserts and rain belts. Since the models do reasonably well in simulating these outstanding features of the mean precipitation field, this prediction probably has some validity. However, as the models generally have difficulty simulating the mean precipitation field in greater detail than this, little confidence is warranted in information about the changes in the hydrologic cycle on smaller spatial scales.

4.3 Transient response

The simulation of the changes in oceanic heat transport can be a significant factor in the evolution of the climate system in climate change experiments where greenhouse gases are gradually increasing. In the present-day ocean, a northward surface current transports a significant amount of heat from the tropical Atlantic to the northern North Atlantic, where the waters cool, become dense, and sink. This is one significant branch of the ocean's global overturning circulation. If this circulation were to weaken, it would result in significant cooling of the northern North Atlantic on the order of a few degrees C. This is in fact what happens in many climate change experiments. In some simulations, the warming of the surface waters of the northern North Atlantic makes them less dense. This inhibits the sinking, slows down the overturning and northward heat transport, and causes cooling. In other simulations, the intensification of the hydrologic cycle discussed above manifests itself in the North Atlantic region as a large increase in precipitation and only a modest increase in evaporation, decreasing the salinity of the surface waters. This also makes them less dense and less prone to sinking, which slows down the overturning, and causes cooling. In still other simulations a combination of these two effects is at work. The cooling counteracts the overall warming, so that the North Atlantic stands out as a region that responds very differently from the rest of the world to increasing greenhouse gases. Because the models do not agree on the mechanisms behind the simulated changes in the North Atlantic circulation, it is too early to assess the robustness of this phenomenon. Moreover, in most climate change experiments that predict an initial weakening of the overturning circulation, it eventually recovers within 100 years or so, so that the North Atlantic region ultimately experiences warming to approximately the same degree as surrounding areas.

5. Future challenges

Major scientific advancement in the area of global change modeling will require investment in three areas:

(1) Inclusion of the biosphere in coupled ocean-atmosphere models. This process is already underway, though the models have not yet developed to the point where meaningful predictions of both the impact of climate change on ecosystems and the role of ecosystems in climate change is possible. Of course, significant improvements in the regional scale predictions of the coupled ocean-atmosphere models are necessary before most interactions between climate and ecosystems can be explored rigorously; however, there is no reason the incorporation of the biosphere into the atmosphere-ocean models cannot occur in parallel with improvements in regional-scale climate simulation.

(2) Improving the dialogue between modeling and observations. Improvements in remote sensing techniques are already beginning to allow for global-scale, high-resolution comparisons of many climate-relevant quantities between models and observations. Once the satellites have been taking measurements for long enough, this will constitute a major advance over the weather station based observations of the past. Detailed satellite observations of cloud properties, in particular, should lead to more realistic representations of sub-grid scale cloud processes in the models. This may lead to more confidence in simulations of cloud feedback and the predicted changes in the hydrologic cycle.

(3) Management of additional computational resources. As computational resources continue their rapid expansion, decisions about how to invest them become even more critical. Ways to invest these resources include increasing the models' resolution, increasing the complexity of the representation of physical processes, or increasing the number or length of climate modeling experiments. Deploying computational resources in one of these areas always means less is available for the other two, so care must be taken in making these trade-offs, with an eye towards a specific scientific objective.

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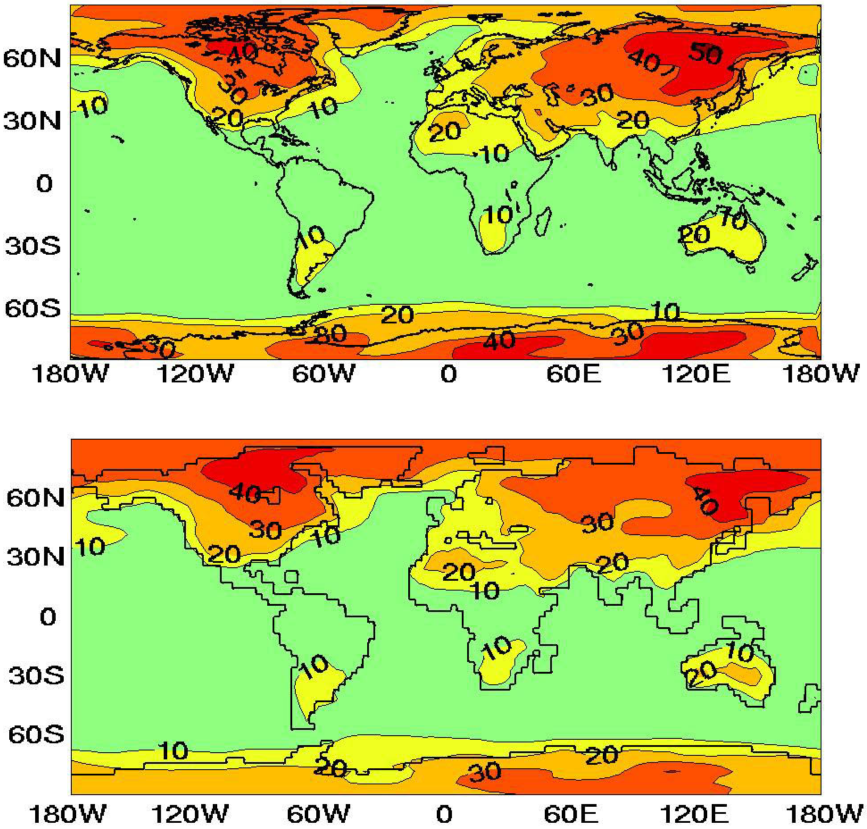
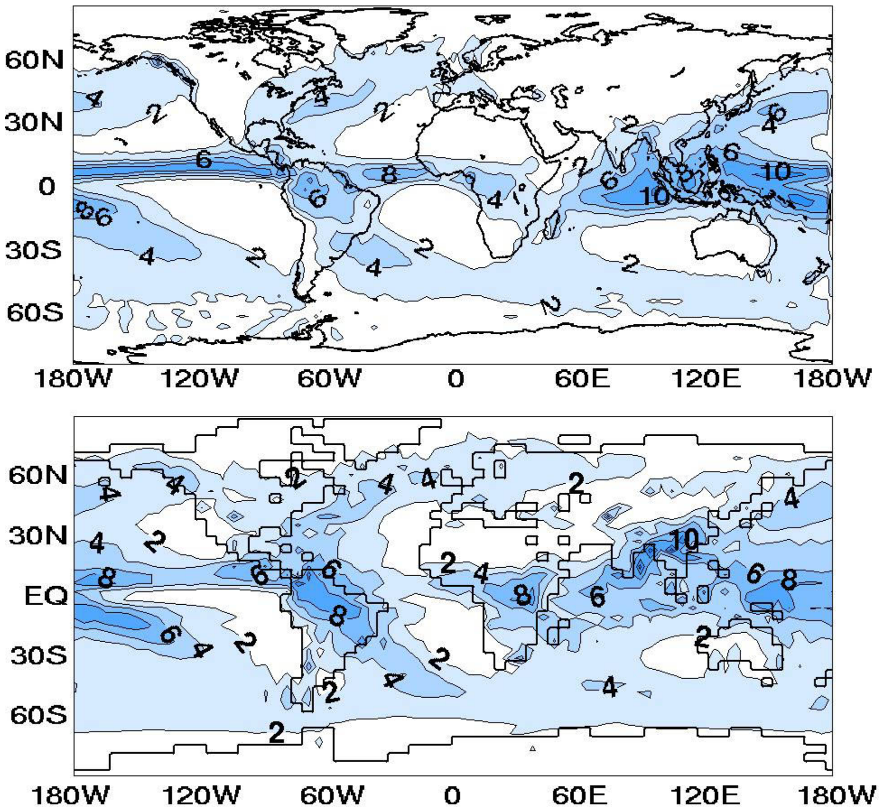


Figure 1. **Top**: The observed amplitude of the seasonal cycle of surface air temperature (degrees C). This quantity provides a measure of the strength of the climate system's response to the annual cycle of sunshine and is calculated by subtracting the minimum temperature of the monthly mean climatology from the maximum temperature at each geographical location. Data source: The National (U.S.) Center for Environmental Prediction (NCEP) re-analysis. **Bottom**: The amplitude of the seasonal cycle of surface air temperature as simulated by the NCAR Community Climate System Model (CCSM). This model consists of interacting atmosphere, ocean, and land components. The model topography shown on the plot gives a general idea of the spatial scales the model is capable of resolving explicitly. In general, model and observation agree well in the magnitude and geographical distribution of the overall pattern.



<u>Figure 2.</u> **Top:** The observed annual-mean precipitation rate (mm/day) based on a 17-year climatology. Data were obtained from rain guages and satellites and were compiled by Xie and Arkin. **Bottom:** The annual-mean precipitation rate simulated by the UCLA Atmospheric General Circulation Model based on a 10-year climatology. The model succeeds in capturing the gross features of the observed precipitation field, including the maxima associated with the tropical rain belts, the mid-latitude storm tracks, as well as the minima associated with the subtropical dry regions. On smaller spatial scales, however, model and observation diverge somewhat in both the magnitude and geographical distribution of the precipitation rate. This model's performance is comparable to other models of similar resolution.