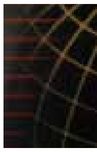
EXECUTIVE SUMMARY

Scientists extensively use mathematical models of Earth's climate, executed on the most powerful computers available, to examine hypotheses about past and present-day climates. Development of climate models is fully consistent with approaches being taken in many other fields of science dealing with very complex systems. These climate simulations provide a framework within which enhanced understanding of climate-relevant processes, along with improved observations, are merged into coherent projections of future climate change. This report describes the models and their ability to simulate current climate.



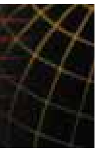
The science of climate modeling has matured through finer spatial resolution, the inclusion of a greater number of physical processes, and comparison to a rapidly expanding array of observations. These models have important strengths and limitations. They successfully simulate a growing set of processes and phenomena; this set intersects with, but does not fully cover, the set of processes and phenomena of central importance for attribution of past climate changes and the projection of future changes. Following is a concise summary of the information in this report, organized around questions from the "Prospectus," which motivated its preparation, and focusing on these strengths and weaknesses.

What are the major components and processes of the climate system that are included in present state-of-the-science climate models, and how do climate models represent these aspects of the climate system?

Chapter 2 describes the four major components of modern coupled climate models: atmosphere, ocean, land surface, and sea ice. The development of each of these individual components raises important questions as to how key physical processes are represented in models, and some of these questions are discussed in this report. Furthermore, strategies used to couple the components into a climate system model are detailed. Development paths for the three U.S. modeling groups that contributed to the 2007 Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment of Climate Change (IPCC 2007) serve as examples. Experience and expert judgment are essential in constructing and evaluating a climate modeling system, so multiple modeling approaches are still needed for full scientific evaluation of the state of the science.

The set of most recent climate simulations, referred to as CMIP3 models and utilized heavily in Working Group 1 and 2 reports of the Fourth IPCC Assessment, have received unprecedented scrutiny by hundreds of investigators in various areas of expertise. Although a number of systematic biases are present across the set of models, more generally the simulation strengths and weaknesses, when compared against the current climate, vary substantially from model to model. From many perspectives, an average over the set of models clearly provides climate simulation superior to any individual model, thus justifying the multimodel approach in many recent attribution and climate projection studies.

Climate modeling has been steadily improving over the past several decades, but the pace has been uneven because several important aspects of the climate system present especially severe challenges to the goal of simulation.



How are changes in the Earth's energy balance incorporated into climate models? How sensitive is the Earth's (modeled) climate to changes in the factors that affect the energy balance?

The Earth's radiant energy balance at the top of the atmosphere helps to determine its climate. Chapter 2 contains a brief description of energy-transfer simulation within models, particularly within the atmospheric component. More important, Chapter 4 includes an extensive discussion about radiative forcing of climate change and climate sensitivity. The response of global mean temperature to a doubling of carbon dioxide remains a useful measure of climate sensitivity. The equilibrium response—the response expected after waiting long enough (many hundreds of years) for the system to reequilibrate—is the most commonly quoted measure. Remaining consistent for three decades, the range of equilibrium climate sensitivity obtained from models is roughly consistent with estimates from observations of recent and past climates. The canonical threefold range of uncertainty, 1.5 to 4.5°C, has evolved very slowly. The lower limit has been nearly unchanged over time, with very few recent models below 2°. Difficulties in simulating Earth's clouds and their response to climate change are the fundamental reasons preventing a reduction in this range in model-generated climate sensitivity.

Other common measures of climate sensitivity measure the climate response on time scales shorter than 100 years. By these measures there is considerably less spread among the models—roughly a factor of two rather than three. The range still is considerable and is not decreasing rapidly, due in part to difficulties in cloud simulation but also to uncertainty in the rate of heat uptake by the oceans. This uncertainty rises in importance when considering the responses on these shorter time scales.

Climate sensitivity in models is subjected to tests using observational constraints. Tests include climate response to volcanic eruptions; aspects of internal climate variability that provide information on the strength of climatic "restoring forces"; the response to the 11-year cycle in solar irradiance; paleoclimatic information, particularly from the peak of the last Ice Age some 20,000 years ago; aspects of the seasonal cycle; and the magnitude of observed warming over the past century. Because each test is subject to limitations in data and complications from feedbacks in the system, they do not provide definitive tests of models' climate sensitivity in isolation. Studies in which multiple tests of model climate responses are considered simultaneously are essential when analyzing these constraints on sensitivity.

Improvements in our confidence in estimates of climate sensitivity are most likely to arise from new data streams such as the satellite platforms now providing a first look at the three-dimensional global distributions of clouds. New and very computationally intensive climate modeling strategies that explicitly resolve some of the smaller scales of motion influencing cloud cover and cloud radiative properties also promise to improve cloud simulations.

How uncertain are climate model results? In what ways has uncertainty in model-based simulation and prediction changed with increased knowledge about the climate system?

Chapter 1 provides an overview of improvement in models in both completeness and in the ability to simulate observed climate. Climate models are compared to observations of the mean climate in a multitude of ways, and their ability to simulate observed climate changes, particularly those of the past century, have been examined extensively. A discussion of metrics that may be used to evaluate model improvement over time is included at the end of Chapter 2, which cautions that no current model is superior to others in all respects, but rather that different models have differing strengths and weaknesses.

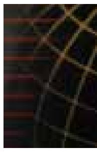
As discussed in Chapter 5, climate models developed in the United States and around the world show many consistent features in their simulations and projections for the future. Accurate simulation of present-day climatology for near-surface temperature and precipitation is necessary for most practical applications of climate modeling. The seasonal cycle and large-scale geographical variations of near-surface temperature are indeed well simulated in recent models, with typical correlations between models and observations of 95% or better.

Climate model simulation of precipitation has improved over time but is still problematic. Correlation between models and observations is 50 to 60% for seasonal means on scales of a few hundred kilometers. Comparing simulated and observed latitude-longitude precipitation maps reveals similarity of magnitudes and patterns in most regions of the globe, with the most striking disagreements occurring in the tropics. In most models, the appearance of the Inter-Tropical Convergence Zone of cloudiness and rainfall in the equatorial Pacific is distorted, and rainfall in the Amazon Basin is substantially underestimated. These errors may prove consequential for a number of model predictions, such as forest uptake of atmospheric CO_2.

Simulation of storms and jet streams in middle latitudes is considered one of the strengths of atmospheric models because the dominant scales involved are reasonably well resolved. As a consequence, there is relatively high confidence in the models' ability to simulate changes in these extratropical storms and jet streams as the climate changes. Deficiencies that still exist may be due partly to insufficient resolution of features such as fronts, to errors in the forcing terms from moist physics, or to inadequacies in simulated interactions between the tropics and midlatitudes or between the stratosphere and the troposphere. These deficiencies are still large enough to impact ocean circulation and some regional climate simulations and projections.

The quality of ocean climate simulations has improved steadily in recent years, owing to better numerical algorithms and more realistic assumptions concerning the mixing occurring on scales smaller than the models' grid. Many of the CMIP3 class of models are able to maintain an overturning circulation in the Atlantic with roughly the observed strength without the artificial correction to air-sea fluxes commonly used in previous generations of models, thus providing a much better foundation for analysis of the circulation's stability. Circulation in the Southern Ocean, thought to be vitally important for oceanic uptake of carbon dioxide from the atmosphere, is sensitive to deficiencies in simulated winds and salinities, but a subset of models is producing realistic circulation in the Southern Ocean as well.

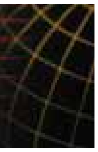
Models forced by the observed well-mixed greenhouse gas concentrations, volcanic aerosols, estimates of variations in solar energy incidence, and anthropogenic aerosol concentrations are able to simulate the recorded 20th Century global mean temperature in a plausible way. Solar variations, observed through direct satellite measurements for the last few decades, do not contribute significantly to warming during that period. Solar variations early in the 20th Century are much less certain but are thought to be a potential contributor to warming in that period.



Uncertainties in the climatic effects of man-made aerosols (liquid and solid particles suspended in the atmosphere) constitute a major stumbling block in quantitative attribution studies and in attempts to use the observational record to constrain climate sensitivity. We do not know how much warming due to greenhouse gases has been cancelled by cooling due to aerosols. Uncertainties related to clouds increase the difficulty in simulating the climatic effects of aerosols, since these aerosols are known to interact with clouds and potentially can change cloud radiative properties and cloud cover.

The possibility that natural variability has been a significant contributor to the detailed time evolution seen in the global temperature record is plausible but still difficult to address with models, given the large differences in characteristics of the natural decadal variability between models. While natural variability may very well be relevant to observed variations on the scale of 10 to 30 years, no models show any hint of generating large enough natural, unforced variability on the 100-year time scale to compete with explanations that the observed century-long warming trend has been predominantly forced.

The observed southward displacement of the Southern Hemisphere storm track and jet stream in recent decades is reasonably well simulated in current models, which show that the displacement is due partly to greenhouse gases but also partly to the presence of the stratospheric ozone hole. Circulation changes in the Northern Hemisphere over the past decades have proven more difficult to capture in current models, perhaps because of more complex interactions between the stratosphere and troposphere in the Northern Hemisphere.



Observations of ocean heat uptake are beginning to provide a direct test of aspects of the ocean circulation directly relevant to climate change simulations. Coupled models provide reasonable simulations of observed heat uptake in the oceans but underestimate the observed sea-level rise over the past decades.

Model simulations of trends in extreme weather typically produce global increases in extreme precipitation and severe drought, with decreases in extreme minimum temperatures and frost days, in general agreement with observations.

Simulations from different state-of-the-science models have not fully converged, however, since different groups approach uncertain model aspects in distinctive ways. This absence of convergence is one useful measure of the state of climate simulation; convergence is to be expected once all climate-relevant processes are simulated in a convincing physically based manner. However, measuring the quality of climate models so the metric used is directly relevant to our confidence in the models' projections of future climate has proven difficult. The most appropriate ways to translate simulation strengths and weaknesses into confidence in climate projections remain a subject of active research.

How well do climate models simulate natural variability and how does variability change over time?

Simulation of climate variations also is described in Chapter 5. Simulations of El Niño oscillations, which have improved substantially in recent years, provide a significant success story for climate models. Most current models spontaneously generate El Niño–Southern Oscillation variability, albeit with varying degrees of realism. Oscillation spatial structure and duration are impressive in a model subset but with a tendency toward too short a period. Bias in the Inter-Tropical Convergence Zone (ITCZ) in coupled models is a major factor preventing further improvement in these models. Projections for future El Niño variability and the state of the Pacific Ocean are centrally important for regional climate change projections throughout the tropics and in North America.

Other aspects of the tropical simulations in current models remain inadequate. The Madden-Julian Oscillation, a feature of the tropics in which precipitation is organized by large-scale eastward-propagating features with periods of roughly 30 to 60 days, is a useful test of simulation credibility. Model performance using this measure is still unsatisfactory. The "double ITCZ–cold tongue bias," in which water is excessively cold near the equator and precipitation splits artificially into two zones straddling the equator, remains as a persistent bias in current coupled atmosphere-ocean models. Projections of tropical climate change are affected adversely by these deficiencies in simulations of the organization of tropical convection. Models typically overpredict light precipitation and underpredict heavy precipitation in both the tropics and middle latitudes, creating potential biases when studying extreme events. Tropical cyclones are poorly resolved by the current generation of global models, but recent results with high-resolution atmosphere-only models and dynamical downscaling provide optimism that the simulation of tropical cyclone climatology will advance rapidly in coming years, as will our understanding of observed variations and trends.

The quality of simulations of low-frequency variability on decadal to multidecadal time scales varies regionally and also from model to model. On average, models do reasonably well in the North Pacific and North Atlantic. In other oceanic regions, lack of data contributes to uncertainty in estimating simulation quality at these low frequencies. A dominant mode of low-frequency variability in the atmosphere, known as northern and southern annular modes, is very well captured in current models. These modes involve north-south displacements of the extratropical storm track and have dominated observed atmospheric circulation trends in recent decades. Because of their ability to simulate annular modes, global climate models do fairly well with interannual variability in polar regions of both hemispheres. They are less successful with daily polar-weather variability, although finer-scale regional simulations do show promise for improved global-model simulations as their resolution increases.

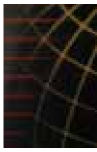
How well do climate models simulate regional climate variability and change?

Chapter 3 describes techniques to downscale coarse-resolution global climate model output to higher resolution for regional applications. These downscaling methodologies fall primarily into two categories. In the first, a higher-resolution, limited-area numerical meteorological model is driven by global climate model output at its lateral boundaries. These dynamical downscaling strategies are beneficial when supplied with appropriate sea-surface and atmospheric boundary conditions, but their value is limited by uncertainties in information supplied by global models. Given the value of multimodel ensembles for larger-scale climate prediction, coordinated downscaling clearly must be performed with a representative set of global model simulations as input, rather than focusing on results from one or two models. Relatively few such multimodel dynamical downscaling studies have been performed to date.

In the second category, empirical relationships between large- and small-scale observations are developed, then applied to global climate model output to provide regional detail. Statistical techniques to produce appropriate small-scale structures from climate simulations are referred to as "statistical downscaling." They can be as effective as high-resolution numerical simulations in providing climate change information to regions unresolved by most current global models. Because of the computational efficiency of these techniques, they can much more easily utilize a full suite of multimodel ensembles. The statistical methods, however, are completely dependent on the accuracy of regional circulation patterns produced by global models. Dynamical models, through higher resolution or better representation of important physical processes, often can improve the physical realism of simulated regional circulation. Thus, the strengths and weaknesses of dynamical modeling and statistical methods often are complementary.

Regional trends in extreme events are not always captured by current models, but it is difficult to assess the significance of these discrepancies and to distinguish between model deficiencies and natural variability.

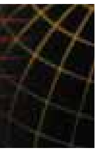
The use of climate model results to assess economic, social, and environmental impacts is becoming more sophisticated, albeit slowly. Simple methods requiring only mean changes in temperature and precipitation to estimate impacts remain popular, but an increasing number of studies are using more detailed information such as the entire distribution of daily or monthly values and extreme outcomes. The mismatch between models' spatial resolution vs the scale of impact-relevant climate features and of impact models remains an impediment for certain applications. Chapter 7 provides several examples of applications using climate model results and downscaling techniques.



What are the tradeoffs to be made in further climate model development (e.g., between increasing spatial/temporal resolution and representing additional physical/biological processes)?

Chapter 6 is devoted to trends in climate model development. With increasing computer power and observational understanding, future models will include both higher resolution and more processes.

Resolution increases most certainly will lead to improved representations of atmospheric and oceanic general circulations. Ocean components of current climate models do not directly simulate the oceans' very energetic motions referred to as "mesoscale eddies." Simulation of these small-scale flow patterns requires horizontal grid sizes of 10 km or smaller. Current oceanic components of climate models are effectively laminar rather than turbulent, and the effects of these eddies must be approximated by imperfect theories. As computer power increases, new models that resolve these eddies will be incorporated into climate models to explore their impact on decadal variability as well as heat and carbon uptake. Similarly, atmospheric general circulation models will evolve to "cloud-resolving models" (CRMs) with spatial resolutions of less than a few kilometers. The hope is that CRMs will provide better results through explicit simulation of many cloud properties now poorly represented on subgrid scales of current atmospheric models. CRMs are not new frameworks but rather are based on models designed for mesoscale storm and cumulus convection simulations.



Models of glacial ice are in their infancy. Glacial models directly coupled to atmosphere-ocean models typically account for only direct melting and accumulation at the surface of ice sheets and not the dynamic discharge due to glacial flow. More-detailed current models typically generate discharges that change only over centuries and millennia. Recent evidence for rapid variations in this glacial outflow indicates that more-realistic glacial models are needed to estimate the evolution of future sea level.

Inclusion of carbon-cycle processes and other biogeochemical cycles is required to transform physical climate models into full Earth system models that incorporate feedbacks influencing greenhouse gas and aerosol concentrations in the atmosphere. Land models that predict vegetation patterns are being developed actively, but the demands of these models on the quality of simulated precipitation patterns ensures that their evolution will be gradual and tied to improvements in the simulation of regional climate. Uncertainties about carbon-feedback processes in the ocean as well as on land, however, must be reduced for more reliable future estimates of climate change.