Executive Summary

The goal of simulating the Earth’s climate with mathematical models, using the most powerful computers available, is valid scientifically and fully consistent with the approaches being taken in many other fields of science dealing with very complex systems. These climate simulations provide the frame within which improved understanding of climate-relevant processes and improved observations are naturally merged into coherent projections of future climate change.

The science of climate models has matured to the point that many aspects of current climate models and simulations are very convincing. These form a growing set that intersects significantly with, but does not completely cover, the set of processes that are centrally important for the attribution of past climate changes and the projection of future climate.

The set of the most recent climate simulations, referred to as the CMIP3 models and utilized heavily in the Working Group 1 and 2 reports of the 4th IPCC Assessment, have received unprecedented scrutiny by hundreds of investigators with differing areas of expertise. While there are a number of systematic biases across the set of models, more generally the strengths and weaknesses of the simulations, when compared against the current climate, vary substantially from model to model. It is clear from many perspectives that an average over the set of models provides a superior climate simulation than any individual model, justifying the multi-model approach taken in many recent attribution and climate projection studies.

The pace of climate model improvement has been steady over the past several decades, but the improvement has understandably been uneven, because several important aspects of the climate system present especially severe challenges to the goal of simulation.

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. However, it has proven difficult to measure the quality of climate models in such a way that the metric used is directly relevant to our confidence in the models’ projections of future climate.   The most appropriate ways of translating the strengths and weaknesses of the simulations into confidence in climate projections remains a subject of active research.

The climate models developed in the US and around the world show many consistent features in their simulations and projections for the future. However, they have not fully converged, since different groups approach uncertain aspects of the models in distinctive ways. This absence of convergence is one useful measure of the state of the science of climate simulation; convergence is to be expected once all climate-relevant processes are simulated in a convincing physically-based manner.

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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 if one waits long enough (many hundreds of years) for the system to re-equilibrate, is the most commonly quoted measure. The range of equilibrium climate sensitivity obtained from models has remained robust for three decades, and roughly consistent with estimates from the observations of recent climates and those from the more distant past. The canonical three-fold range of uncertainty, 1.5-4.5 degrees Centigrade, has evolved very slowly. The lower limit has been particularly robust over time, with very few recent models below 2 degrees. The difficulty in simulating the Earth's clouds and their response to climate change are the fundamental reason why it has proven difficult to reduce the range of uncertainty in model-generated climate sensitivity.

Other common measures of climate sensitivity are of more relevance to the 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. Uncertainty still remains considerable and is not decreasing rapidly, due in part to the difficulty of cloud simulation but also to uncertainty in the rate of heat uptake by the oceans which rises in importance when considering the responses on these shorter time scales.

Improvements in our confidence in estimates of the sensitivity of climate are most likely to arise from new data streams, such as satellite platforms that are now providing a first look at the 3-dimensional global distributions of clouds, and new, very computationally intensive, climate modeling strategies that explicitly resolve some of the smaller scales of motion that help control cloud cover and cloud radiative properties.

Regional modeling and downscaling

Simulations by limited-area models, stretched grid models and uniformly high-resolution atmospheric models forced by specified oceanic and sea ice conditions are all capable of resolving phenomena too fine for standard atmosphere-ocean GCMs, such as precipitation influenced by mountains and ocean-land interaction in coastal zones. These dynamical downscaling strategies are beneficial when supplied with appropriate sea-surface and atmospheric boundary conditions, but their value is limited by uncertainties in the information supplied by the global models. Given the value of multi-model ensembles for larger-scale climate prediction, it is clear that downscaling must presently be performed in a coordinated fashion with a representative set of global model simulations as input, rather than focusing on the results from one or two models. Relatively few such multi-model dynamical downscaling studies have been performed to date.

Statistical techniques to produce appropriate small-scale structures from climate simulations, referred to as “statistical downscaling”, can be as effective as high-resolution numerical simulations in providing climate change information to regions unresolved by most current global models, and because of their computational efficiency they can much more easily utilize a full suite of multi-model ensembles. However, the statistical methods are completely dependent on the accuracy of the regional circulation patterns produced by the global models, whereas regional models, through higher resolution and/or better representation of important physical processes, can often improve the physical realism of the simulated regional circulation. Thus, the strengths and weaknesses of the regional modeling and statistical methods are often complimentary.

The quality of climate simulations

Accurate simulation of the 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.

AOGCM simulation of precipitation has improved over time but is still problematic. The correlation between models and observations is 50-60% for seasonal means on scales of a few hundred kilometers. Comparing simulated and observed latitude-longitude maps of precipitation 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 CO2.

The simulation of the storms and jet streams in middle latitudes are 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 models’ ability to simulate the changes in these extratropical storms and jet streams as the climate changes. The deficiencies that still exist may be partly due to insufficient resolution to resolve features such as fronts or to inadequacies in the simulated interactions between the tropics and midlatitudes or between the stratosphere and the troposphere. These deficiencies are still large enough to impact the ocean circulation and some regional climate simulations and projections.

A dominant mode of low-frequency variability in the atmosphere known as the northern and southern annular modes, are very well captured in current models. These modes involve north/south displacements of the extratropical storm track and dominate the observed trends in atmospheric circulation in recent decades.Because of their ability to simulate the annular modes, global climate models simulate fairly well the interannual variability in the polar regions of both hemispheres. They are less successful at simulating daily polar-weather variability, though finer scale regional simulations do simulate polar weather well, thus showing promise for improved global-model simulations as their resolution increases.

In the tropics, simulations in current models are less credible. The Madden-Julian oscillation, a feature of the tropics in which the precipitation is organized by large-scale eastward propagating features with periods of roughly 30-60 days, is a useful test of simulation credibility in the tropics. 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 adversely affected 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 present 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 the coming years, as will our understanding of observed variations and trends.

Land surface modeling for climate simulation has increased markedly in sophistication over the past 25 years, with increasing detail and range of processes included in the biological, chemical and physical behavior simulated in the terrestrial portion of the climate system. Systematic programs comparing land models have gradually led to greater agreement between land models and observations, in part because a greater variety of observations have been used to understand and constrain their behavior.

Land models that predict vegetation patterns are being actively developed, but the demands that these models make on the quality of the simulated precipitation patterns ensures that the their evolution will be gradual and tied to improvements in the regional climate simulations.

The quality of ocean climate simulations has improved steadily in recent years, owing to improved 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 approximately the observed strength without the artificial correction to the air-sea fluxes commonly in use in previous generations of models, providing a much better foundation for analysis of the stability of this circulation.

The circulation in the Southern Oceans, thought to be of vital importance for the oceanic uptake of carbon dioxide from the atmosphere, is sensitive to deficiencies in the simulated winds and salinities, but a subset of the models are producing realistic circulation in the Southern Ocean as well

Simulations of El Nino oscillations provide a significant success story for climate models, as these have improved substantially in recent years. Most current models spontaneously generate El Nino-Southern Oscillation variability, albeit with varying degrees of realism. The spatial structure and period of the oscillations is impressive in a subset of the models, but with a tendency towards too short a period. The bias in the intertropical convergence zone in the coupled models is a major factor preventing further improvement in these models. Projections for the future of El-Nino variability and the state of the Pacific Ocean are of central importance for regional climate change projections throughout the tropics and in North America.

The quality of simulations of low frequency variability on decadal to multi-decadal time scales varies regionally and also varies substantially from model to model. On average, the models do reasonably well in the North Pacific and North Atlantic. In other oceanic regions, data paucity contributes to the uncertainty in the estimation of the quality of the simulations at these low frequencies.

The ocean components of current climate models do not directly simulate the very energetic motions in the oceans referred to as “meso-scale eddies” . The simulation of these small scale flow patterns requires horizontal grid sizes of 10km 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.

Models of glacial ice are in their infancy. Glacial models directly coupled to atmosphere-ocean models typically only account for direct melting and accumulation at the surface of the ice-sheets and not the dynamic discharge due to glacial flow. More detailed current models that incorporate this discharge 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.

Simulation of 20th century trends

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

Uncertainties in the climatic effects of man-made aerosols (liquid and solid particles suspended in the atmosphere) are 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 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 between models in the characteristics of the natural decadal variability that they generate. While natural variability may very well be relevant to observed variations on the scale of 10-30 years, no models show any hint of generating large enough natural, unforced variability on the 100 year time scale that would compete with explanations of the observed century-long warming trend as being 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 it is partly due to greenhouse gases but also partly due to the presence of the ozone hole in the stratosphere. Northern Hemisphere circulation changes over the past decades have proven more difficult to capture in current models, perhaps due to the more complex interactions between the stratosphere and the 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 the 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, and decreases in extreme minimum temperatures and frost days, in general agreement with observations.

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 utilizing more detailed information, such as the entire distribution of daily or monthly values and extreme outcomes. The mismatch between the spatial resolution of models and the scale of impacts-relevant climate features and of impacts models remains an impediment for certain applications.