

Narrowing Uncertainty in Global Climate Change

by Chris Forest, Mort Webster, and John Reilly

Unknowns hamper initiating climate-mitigation policies

Experts disagree about how climate might change in the future, but they generally agree that great uncertainty exists in any projection of future climate. The Joint Program on the Science and Policy of Global Change, an interdisciplinary program at the Massachusetts Institute of Technology (MIT), has sought since its start in 1991 to better quantify that uncertainty. The program's multiyear effort to develop the capability to make probabilistic projections of future climate change is now bearing fruit.

Why focus on simply describing uncertainty, when the scientific objective usually centers on how to reduce it? Our motivation is that almost all the decisions we make as individuals and as a society are made under uncertainty. Decisions we make with regard to climate—whether to reduce emissions or not, and by how much—will also involve uncertainty. However, those decisions can be improved with an accurate description of the uncertainty inherent in the climate system. A vigorous scientific research program will undoubtedly improve our understanding of the climate system, and may reduce uncertainty after years or decades of observation and measurement. But some, and maybe much, of the uncertainty we face in projecting decades into the future is irreducible.

Even as the necessary research and measurement proceed, we need to decide how much we should begin deflecting the world's economy from a path that would likely more than double the concentration of greenhouse gases (GHGs) by the end of this century. As new data become available, we will need to revise our estimate of

uncertainty, and that, in turn, may involve a midcourse correction of policies designed to address climate change.

The modeling system developed in the Joint Program, the MIT Integrated Global Systems Model (IGSM), calculates how much a given emissions-reduction policy will likely reduce the odds of serious impacts from global climate change. The analytical model takes uncertain inputs that affect economic activities, GHG emissions, and the climate system's response and calculates the probability of specific outcomes. Thus, it forecasts possible temperature increases for the next 100 years and the probability that each will occur. Subsequent runs using lower emissions show how emissions-control policies could change the probabilities.

For decades, pervasive uncertainty has stymied the climate-change policy-making process. How much will temperature change, and how soon? How sensitive is the climate to GHGs in the atmosphere? And what impact will policies to limit emissions actually have on future temperatures? Recognizing that it may not be possible to decide who is right in these debates may not stop them, but describing likelihood more precisely can help decision-makers focus on how to avoid those serious adverse effects that have a substantial chance of occurring.

The MIT IGSM is a set of linked computer models that simulate economic growth and its associated emissions, the flows of GHGs into and out of the land masses and oceans, chemical reactions in the atmosphere, climate dynamics, and changes in natural terrestrial ecosystems. The models and the processes they simulate—each with its own uncertainties—interact, with outputs from one serving as inputs for another (Figure 3).

Uncertainty calculations involve quantifying the likelihood that each of the many parameters that drive the model will occur, from economic growth and energy efficiency improvement to emissions of methane from agriculture and of nitrous oxides from industry. Defining the uncertainties in a critical process involves estimating a probability density function (pdf)—which describes the

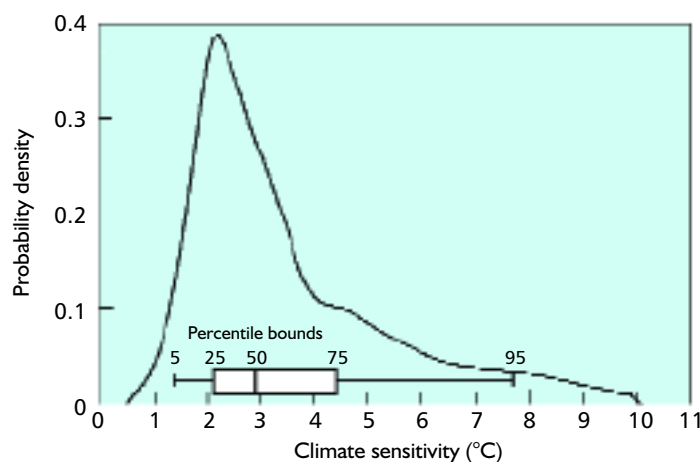


Figure 1. The likelihood of a change in equilibrium global mean surface temperature caused by a doubling of atmospheric carbon dioxide shows a mean of 3.5 °C and a median of 2.9 °C.

probability of events occurring over time—for the parameter or parameters of that process. For the climate system, this mathematical modeling involves processes that affect climate sensitivity, the uptake of heat and carbon dioxide by the oceans, and the role of aerosols and other pollutants in climate. Some of these parameters—the reflective sulfate aerosols, for example—have likely contributed a cooling effect that has offset warming caused by GHGs, at least partially.

Figure 1 shows a sample pdf for climate sensitivity. Climate sensitivity is the change in global mean surface temperature caused by a doubling of carbon dioxide in the atmosphere that would occur if the Earth system would fully adjust to the higher concentrations of CO₂. It is widely used to summarize how different climate models respond to external forcings. Estimating this pdf involves a statistical exercise that finds the parameter combinations that, when used in the MIT IGSM, best fit the most recent 50 years of atmospheric and oceanic temperature measurements, as well as the calculated interrelationships among climate sensitivity, the effects of aerosols, and the rate at which the deep oceans take up heat.

Uncertainties represented with similar pdfs for other uncertain parameters in the Earth system—the ocean, atmosphere, and biosphere, which all contribute to climate change—and the economic model are propagated through the IGSM by running the model many times with varying values for each parameter. In every run, the model uses a numerical sampling method to choose a value for each parameter. The sampling method is constructed so that each discrete value for a variable represents an equal likelihood drawn from the input pdf. Thus, each parameter set has an equal probability of occurring.

For each set of input parameter values, the IGSM run produces a different result for outcomes that include predicted temperature change and sea-level rise. It takes a cluster of 16 computer processors operating nonstop for about a month to produce 250 runs—enough to get a good approximation of the distribution of outcomes that would be

obtained if the model were run thousands of times. Taking the results from all the runs yields a range of values for a given outcome, with equal probability of occurrence for each value. The uncertainties of the input parameters are, thus, reflected in the uncertainty of the results.

Figure 2 shows sample results for the calculated temperature change between 1990 and 2100, presented by latitude. The solid lines show results from “business as usual” assumptions. Ninety-five percent of the calculated values fall between the lines marked “upper 95% bound” and “lower 95% bound.” Only 5% of the values are outside those bounds, with 2.5% falling above and 2.5% falling below. At the median, half of the temperature values are above and half are below.

As expected, predicted temperature change varies with latitude. Estimated warming—as well as the associated uncertainty—is significantly greater near the poles than in the tropics. The upper bound is especially worrisome at the poles. Because 2.5% of the model results were above that bound, the data suggest that a 1 in 40 chance exists that warming will exceed 8 °C at the South Pole and 12 °C at the North Pole. Warming is greater at the North Pole because the smaller area of Arctic Sea ice

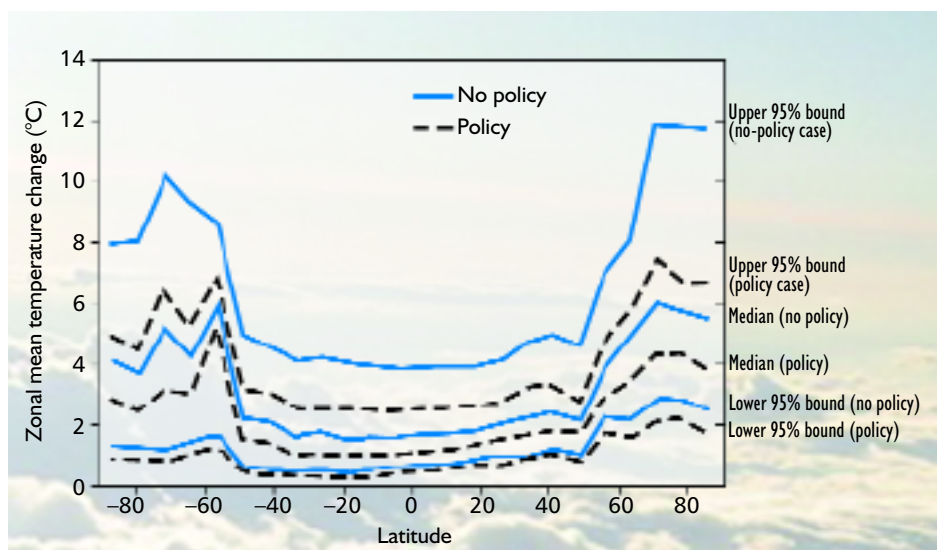


Figure 2. Projected temperature increases between 1990 and 2100 exceed 8 °C for the South Pole and 12 °C for the North Pole with no policy of significantly lower emissions and half those increases with such a policy.

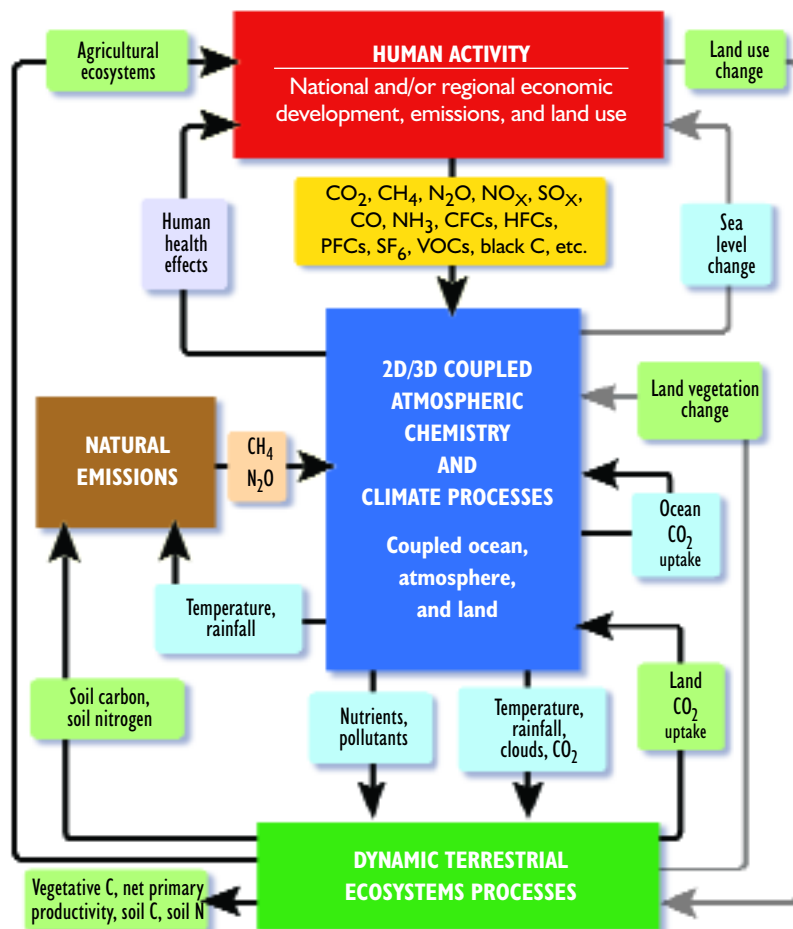


Figure 3. In the integrated global system model, the human and natural emissions model outputs are driving forces for the atmospheric chemistry and climate model, whose outputs drive a terrestrial ecosystems model.

ture increase. Most important, it cuts the unlikely-but-possible high-end temperature results almost in half.

The larger reduction of the worst-case outcomes reflects the nature of the stringent policy. It is a cap on emissions over the period. Emissions uncertainty is an important contributor to overall uncertainty. An emissions cap, if effectively implemented, would obviously eliminate the possibility of high emissions. However, it would not have any effect if little growth in emissions had occurred, whether by good fortune (technology) or bad (poor economic growth). A different form of policy—a pollution tax, for example—would not cap emissions in an absolute sense and would more likely shift the entire temperature distribution lower.

The implications of changes in pdfs and abstract concepts such as global average surface temperature are hard for even experts to grasp. Ideally, we could further describe these climate-system responses in terms of their impacts on agriculture, human health, and fragile ecosystems. However, the ability to represent such effects probabilistically remains for the future. In the meantime, we have attempted to identify some critical values and the likelihood of exceeding them, as portrayed in the table. The left column identifies some specific, serious changes that could occur. The next three columns present the odds that those changes will occur assuming no emissions policy, a relatively lenient emissions-control policy, and the stringent policy. Although the lenient policy helps, the more-stringent policy dramatically reduces the probability of the selected outcomes. One lesson of this work is the impossibility of completely eliminating a risk. We can only reduce the chances of it occurring.

This effort is an early attempt to assimilate the available information on the Earth system and the economic forces that relate to future climate change, and to describe quantitatively the uncertainty in future projections. Although such exercises guide our understanding of the likely conditions of future climate, much work remains to be done, and there will always be unknowns that defy quantification. Unchanging physical laws control natural processes. The challenge is to use available data to constrain parameters of the Earth system when we have an incomplete understanding of all the processes that create variability in the climate system.

A debate continues about how to quantify uncertainty in human systems—for example, economic growth and emissions projections. Under the best of circumstances, such efforts require the judgment of experts on future growth and technology possibilities. Past response and the behavior of the economy are our observations, but future

means less reflected sunlight.

How might emission-control policies change those outcomes? The dashed lines in the figure show results assuming an emissions-control policy that, by our best estimate of conditions, would stabilize atmospheric concentrations of carbon dioxide at 550 ppm. Such a policy would require incredibly efficient vehicles and homes, and the use of noncarbon fuels or carbon sequestration. But the reduction in emissions significantly reduces the tempera-

Lowering the risks of serious climate change

2000–2100 change	Without policy	750-ppm policy	550-ppm policy
>6.8 °F (3.8 °C) global warming	1 in 10	1 in 29	< 1 in 250
20% Arctic Sea ice decrease	1 in 4	1 in 5	< 1 in 100
>10 °F (5.6 °C) Alaska warming	1 in 3	1 in 4	Negligible
>2 ft (0.6 m) sea-level rise	1 in 6	1 in 20	Negligible

The probability that the serious changes listed in column 1 could occur over a 100-year period if there were no policy to stabilize atmospheric concentrations of carbon dioxide, with a relatively lenient 750-ppm policy, and with a stringent 550-ppm policy.

response is not constrained in the same way that physical properties constrain the response of natural systems.

At the same time, the Earth system is so complex—and our time series of good observations so short relative to the time scale on which the system operates—that our ability to know the behavior of this system may be quite limited. This means that possible responses are not captured in a distribution created with a model that includes only what we now know about the Earth system's behavior. One of the pressing challenges is to understand the processes that have led to the previous relatively abrupt change of several degrees Celsius within a decade or so found in the paleorecord of Earth. Current models do not provide an explanation for such changes.

Further Reading

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B I O G R A P H Y

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