Climate researchers are finally homing in on just how bad greenhouse warming could get—and it seems increasingly unlikely that we will escape with a mild warming

Three Degrees of Consensus

Paris—Decades of climate studies have made some progress. Researchers have convinced themselves that the world has indeed warmed by 0.6°C during the past century. And they have concluded that human activities—mostly burning fossil fuels to produce the greenhouse gas carbon dioxide (CO_2)—have caused most of that warming. But how warm could it get? How bad is the greenhouse threat anyway?

For 25 years, official assessments of climate science have been consistently vague on future warming. In report after report, estimates of climate sensitivity, or how much a given increase in atmospheric CO_2 will warm the world, fall into the same subjective range. At the low end, doubling CO_2—the traditional benchmark—might eventually warm the world by a modest 1.5°C, or even less. At the other extreme, temperatures might soar by a scorching 4.5°, or more warming might be possible, given all the uncertainties.

At an international workshop* here late last month on climate sensitivity, climatic wishy-washiness seemed to be on the wane. "We've gone from hand waving to real understanding," said climate researcher Alan Robock of Rutgers University in New Brunswick, New Jersey. Increasingly sophisticated climate models seem to be converging on a most probable sensitivity. By running a model dozens of times under varying conditions, scientists are beginning to pin down statistically the true uncertainty of the models' climate sensitivity. And studies of natural climate changes from the last century to the last ice age are also yielding climate sensitivities.

Although the next international assessment is not due out until 2007, workshop participants are already reaching a growing consensus for a moderately strong climate sensitivity. "Almost all the evidence points to 3°C" as the most likely amount of warming for a doubling of CO_2, said Robock. That kind of sensitivity could make for a dangerous warming by century's end, when CO_2 may have doubled. At the same time, most attendees doubted that climate's sensitivity to doubled CO_2 could be much less than 1.5°C. That would rule out the feeble greenhouse warming espoused by some greenhouse contrarians. But at the high and especially dangerous end of climate sensitivity, confidence faltered; an upper limit to possible climate sensitivity remains highly uncertain.

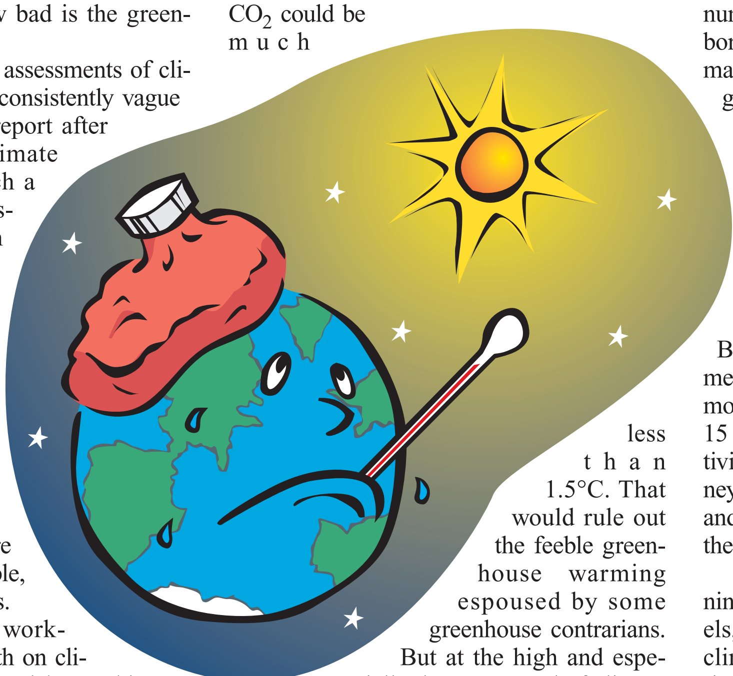


ILLUSTRATION: TIM SMITH

Hand-waving climate models

As climate modeler Syukuro Manabe of Princeton University tells it, formal assessment of climate sensitivity got off to a shaky start. In the summer of 1979, the late Jule Charney convened a committee of fellow meteorological luminaries on Cape Cod to prepare a report for the National Academy of Sciences on the possible effects of increased amounts of atmospheric CO_2 on climate. None of the committee members actually did greenhouse modeling themselves, so Charney called in the only two American researchers modeling greenhouse warming, Manabe and James Hansen of NASA's Goddard Institute for Climate Studies (GISS) in New York City.

On the first day of deliberations, Manabe told the committee that his model warmed 2°C when CO_2 was doubled. The next day Hansen said his model had recently gotten 4°C for a doubling. According to Manabe, Charney chose 0.5°C as a not-unreasonable margin of error, subtracted it from Manabe's number, and added it to Hansen's. Thus was born the 1.5°C-to-4.5°C range of likely climate sensitivity that has appeared in every greenhouse assessment since, including the three by the Intergovernmental Panel on Climate Change (IPCC). More than one researcher at the workshop called Charney's now-enshrined range and its attached best estimate of 3°C so much hand waving.

Model convergence, finally?

By the time of the IPCC's second assessment report in 1995, the number of climate models available had increased to 13. After 15 years of model development, their sensitivities still spread pretty much across Charney's 1.5°C-to-4.5°C range. By IPCC's third and most recent assessment report in 2001, the model-defined range still hadn't budged.

Now model sensitivities may be beginning to converge. "The range of these models, at least, appears to be narrowed," said climate modeler Gerald Meehl of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, after polling eight of the 14 models expected to be included in the IPCC' s next assessment. The sensitivities of the 14 models in the previous assessment ranged from 2.0°C to 5.1°C, but the span of the eight currently available models is only 2.6°C to 4.0°C, Meehl found.

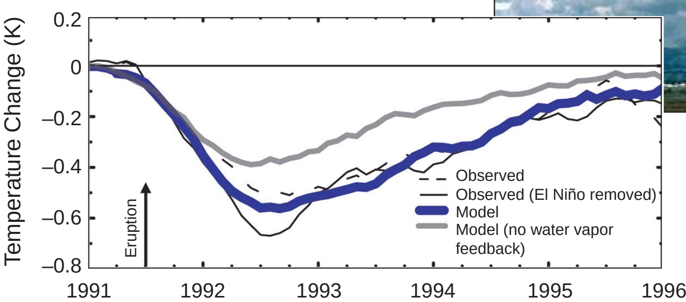
If this limited sampling really has detected a narrowing range, modelers believe there's a good reason for it: More-powerful computers and a better understanding of atmospheric processes are making their models more realistic. For example, researchers at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey, recently adopted a better way of calculating the thickness of the bottommost atmospheric layer—the boundary layer—where clouds form that are crucial to the planet's heat bal-

* Workshop on Climate Sensitivity of the Intergovernmental Panel on Climate Change Working Group I, 26–29 July 2004, Paris.

ance. When they made the change, the model's sensitivity dropped from a hefty 4.5ºC to a more mainstream 2.8ºC, said Ronald Stouffer, who works at GFDL. Now the three leading U.S. climate models—NCAR's, GFDL's, and GISS's—have converged on a sensitivity of 2.5ºC to 3.0ºC. They once differed by a factor of 2.

Less-uncertain modeling

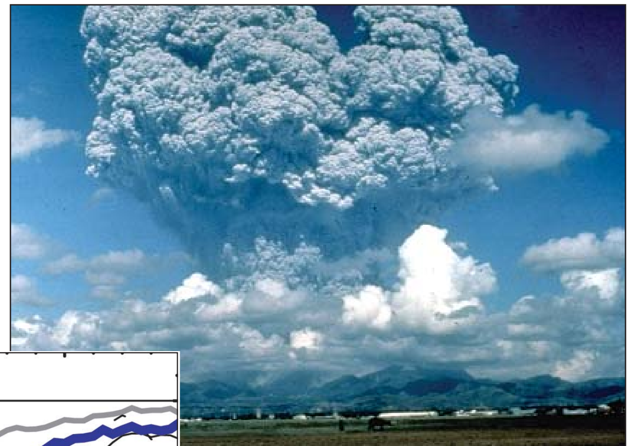
If computer models are increasingly brewing up similar numbers, however, they sometimes disagree sharply about the physical processes that produce them. "Are we getting [similar sensitivities] for the same reason? The answer is clearly no," Jeffrey Kiehl of NCAR said of the NCAR and GFDL models. The problems come from processes called feedbacks, which can amplify or dampen the warming effect of greenhouse gases.



The biggest uncertainties have to do with clouds. The NCAR and GFDL models might agree about clouds' net effect on the planet's energy budget as CO_2 doubles, Kiehl noted. But they get their similar numbers by assuming different mixes of cloud properties. As CO_2 levels increase, clouds in both models reflect more shorter-wavelength radiation, but the GFDL model's increase is three times that of the NCAR model. The NCAR model increases the amount of low-level clouds, whereas the GFDL model decreases it. And much of the United States gets wetter in the NCAR model when it gets drier in the GFDL model.

In some cases, such widely varying assumptions about what is going on may have huge effects on models' estimates of sensitivity; in others, none at all. To find out, researchers are borrowing a technique weather forecasters use to quantify uncertainties in their models. At the workshop and in this week's issue of *Nature*, James Murphy of the Hadley Center for Climate Prediction and Research in Exeter, U.K., and colleagues described how they altered a total of 29 key model parameters one at a time—variables that control key physical properties of the model, such as the behavior of clouds, the boundary layer, atmospheric convection, and winds. Murphy and his team let each parameter in the Hadley Center model vary over a range of values deemed reasonable by a team of experts. Then the modelers ran simulations of present-day and doubled-CO_2 climates using each altered version of the model.

Using this "perturbed physics" approach to generate a curve of the probability of a whole range of climate sensitivities (see figure), the Hadley group found a sensitivity a bit higher than they would have gotten by simply polling the eight independently built models. Their estimates ranged from 2.4ºC to 5.4ºC (with 5% to 95% confidence intervals), with a most probable climate sensitivity of 3.2ºC. In a nearly completed extension of the method, many model parameters are being varied at once, Murphy reported at the workshop. That is dropping the range and the most probable value slightly, making them similar to the eight-model value as well as Charney's best guess.



Volcanic chill. Debris from Pinatubo (*above*) blocked the sun and chilled the world (*left*), thanks in part to the amplifying effect of water vapor.

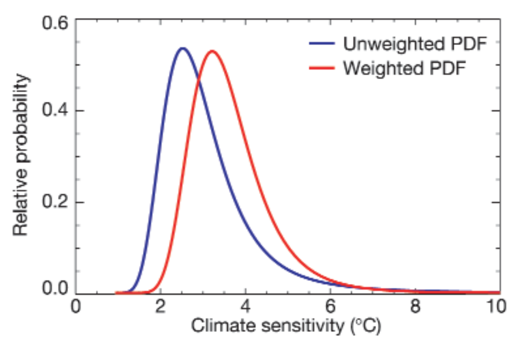
Murphy isn't claiming they have a panacea. "We don't want to give a sense of excessive precision," he says. The perturbed physics approach doesn't account for many uncertainties. For example, decisions such as the amount of geographic detail to build into the model introduce a plethora of uncertainties, as does the model's ocean. Like all model oceans used to estimate climate sensitivity, it has been simplified to the point of having no currents in order to make the extensive simulations computationally tractable.

Looking back

Faced with so many caveats, workshop attendees turned their attention to what may be the ultimate reality check for climate models: the past of Earth itself. Although no previous change in Earth's climate is a perfect analog for the coming greenhouse warming, researchers say modeling paleoclimate can offer valuable clues to sensitivity. After all, all the relevant processes were at work in the past, right down to the formation of the smallest cloud droplet.

One telling example from the recent past was the cataclysmic eruption of Mount Pinatubo in the Philippines in 1991. The debris it blew into the stratosphere, which stayed there for more than 2 years, was closely monitored from orbit and the ground, as was the global cooling that resulted from the debris blocking the sun. Conveniently, models show that Earth's climate system generally does not distinguish between a shift in its energy budget brought on by changing amounts of greenhouse gases and one caused by a change in the amount of solar energy allowed to enter. From the magnitude and duration of the Pinatubo cooling, climate researcher Thomas Wigley of NCAR and his colleagues have recently estimated Earth's sensitivity to a CO_2 doubling as 3.0ºC. A similar calculation for the eruption of Agung in 1963 yielded a sensitivity of 2.8ºC. And estimates from the five largest eruptions of the 20th century would rule out a climate sensitivity of less than 1.5ºC.

Estimates from such a brief shock to the climate system would not include more sluggish climate system feedbacks, such as the expansion of ice cover that reflects radiation, thereby cooling the climate. But the globally dominant feedbacks from water vapor and clouds would have had time to work. Water vapor is a powerful greenhouse gas that's more abundant at higher temperatures, whereas clouds can cool or warm by intercepting radiant energy.



Probably warm. Running a climate model over the full range of parameter uncertainty suggests that climate sensitivity is most likely a moderately high 3.2°C (red peak).

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More climate feedbacks come into play over centuries rather than years of climate change. So climate researchers Gabriele Hegerl and Thomas Crowley of Duke University in Durham, North Carolina, considered the climate effects from 1270 to 1850 produced by three climate drivers: changes in solar brightness, calculated from sunspot numbers; changing amounts of greenhouse gases, recorded in ice cores; and volcanic shading, also recorded in ice cores. They put these varying climate drivers in a simple model whose climate sensitivity could be varied over a wide range. They then compared the simulated temperatures over the period with temperatures recorded in tree rings and other proxy climate records around the Northern Hemisphere.

The closest matches to observed temperatures came with sensitivities of 1.5ºC to 3.0ºC, although a range of 1.0ºC to 5.5ºC was possible. Other estimates of climate sensitivity on a time scale of centuries to millennia have generally fallen in the 2ºC-to-4ºC range, Hegerl noted, although all would benefit from better estimates of past climate drivers.

The biggest change in atmospheric CO_2 in recent times came in the depths of the last ice age, 20,000 years ago, which should provide the best chance to pick the greenhouse signal out of climatic noise. So Thomas Schneider von Deimling and colleagues at the Potsdam Institute for Climate Impact Research (PIK) in Germany have estimated climate sensitivity by modeling the temperature at the time using the perturbed-physics approach. As Stefan Rahmstorf of PIK explained at the workshop, they ran their intermediate complexity model using changing CO_2 levels, as recorded in ice cores. Then they compared model-simulated temperatures with temperatures recorded in marine sediments. Their best estimate of sensitivity is 2.1ºC to 3.6ºC, with a range of 1.5ºC to 4.7ºC.

More confidence

In organizing the Paris workshop, the IPCC was not yet asking for a formal conclusion on climate sensitivity. But participants clearly believed that they could strengthen the traditional Charney range, at least at the low end and for the best estimate. At the high end of climate sensitivity, however, most participants threw up their hands. The calculation of sensitivity probabilities goes highly nonlinear at the high end, producing a small but statistically real chance of an extreme warming. This led to calls for more tests of models against real climate. They would include not just present-day climate but a variety of challenges, such as the details of El Niño events and Pinatubo's cooling.

Otherwise, the sense of the 75 or so scientists in attendance seemed to be that Charney's range is holding up amazingly well, possibly by luck. The lower bound of 1.5ºC is now a much firmer one; it is very unlikely that climate sensitivity is lower than that, most would say. Over the past decade, some contrarians have used satellite observations to argue that the warming has been minimal, suggesting a relatively insensitive climate system. Contrarians have also proposed as-yet-unidentified feedbacks, usually involving water vapor, that could counteract most of the greenhouse warming to produce a sensitivity of 0.5ºC or less. But the preferred lower bound would rule out such claims.

Most meeting-goers polled by *Science* generally agreed on a most probable sensitivity of around 3ºC, give or take a half-degree or so. With three complementary approaches—a collection of expert-designed independent models, a thoroughly varied single model, and paleoclimates over a range of time scales—all pointing to sensitivities in the same vicinity, the middle of the canonical range is looking like a good bet. Support for such a strong sensitivity ups the odds that the warming at the end of this century will be dangerous for flora, fauna, and humankind. Charney, it seems, could have said he told us so. –RICHARD A. KERR

Quantum Information Theory

A General Surrenders the Field, But Black Hole Battle Rages On

Stephen Hawking may have changed his mind, but questions about the fate of information continue to expose fault lines between relativity and quantum theories

Take one set of the *Encyclopedia Britannica*. Dump it into an average-sized black hole. Watch and wait. What happens? And who cares?

Physicists care, you might have thought, reading last month's breathless headlines from a conference in Dublin, Ireland. There, Stephen Hawking announced that, after proclaiming for 30 years that black holes destroy information, he had decided they don't (*Science*, 30 July, p. 586). All of which, you might well have concluded, seems a lot like debating how many angels can dance on the head of a pin.

Yet arguments about what a black hole does with information hold physicists transfixed. "The question is incredibly interesting," says Andrew Strominger, a string theorist at Harvard University. "It's one of the three or four most important puzzles in physics." That's because it gives rise to a paradox that goes to the heart of the conflict between two pillars of physics: quantum theory and general relativity. Resolve the paradox, and you might be on your way to resolving the clash between those two theories.

Eternal darkness? Spherical "event horizon" marks the region where a black hole's gravity grows so intense that even light can't escape. But is the point of no return a one-way street?

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