Climate researchers are grappling with a growing appreciation of climate prediction's large and perhaps unresolvable uncertainties, while remaining steadfast that the threat justifies action

Rising Global Temperature, Rising Uncertainty

CLEARING THE AIR

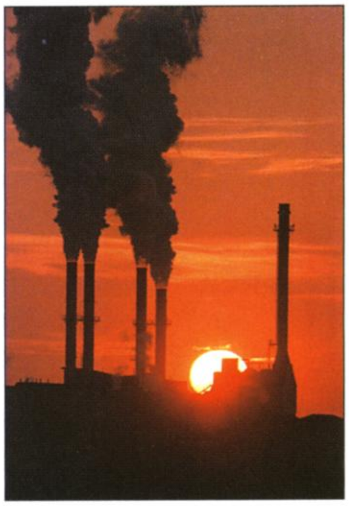
As policy-makers deal with uncertainties in greenhouse models (p. 192), they may find some lessons in the lingering effects of acid rain long after controls were imposed (p. 195).

▶GLOBAL WARMING

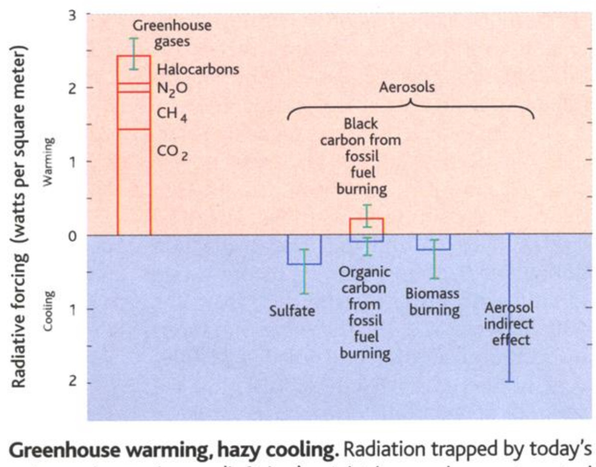
ACID RAIN

The headlines in January were dramatic. "Scientists Issue Dire Prediction on Warming; Faster Climate Shift Portends Global Calamity This Century," said *The Washington Post*. "Warming of Earth Raises New Alarm," cried the *International Herald Tribune*. The source of all this media excitement was a dramatic increase in the worst-case projections of climate change over the next century. The latest report from the United Nations–sponsored Intergovernmental Panel on Climate Change (IPCC)—the closest thing to a global scientific consensus in the contentious business of climate forecasting—said the world could be as much as 5.8°C warmer in 2100 than it is today. Five years ago, the panel set the upper end of the range at 3.5°C. Climatologists, however, were more impressed by something that drew little public notice: The range of the IPCC's projections has actually widened over the past 5 years.

To many climate modelers, this is not surprising. Climate forecasting, after all, is still in its infancy, and the models rely on a sparse database: a mere 100 years of global temperatures. Most agree that this database now shows that the world has warmed over the past century and that greenhouse gases are the prime suspects. But while new knowledge gathered since the IPCC's last report in 1995 has increased many researchers' confidence in the models, in some vital areas, uncertainties have actually grown. "It's extremely hard to tell whether the models have improved" in the past 5 years, says climatologist Gerald North of Texas A&M University in College Station; "the uncertainties are large." Climate modeler Peter Stone of the Massachusetts Institute of Technology says, "The major [climate prediction] uncertainties have not been reduced at all." And cloud physicist Robert Charlson, professor emeritus at the University of Washington, Seattle, adds: "To make it sound like we understand climate is not right."



In the politically charged atmosphere of climate forecasting, uncertainties are often seized upon as excuses for inaction. That worries many of the researchers who believe the stubborn uncertainties in climate forecasting are being downplayed. Most of them see a need to begin controlling greenhouse gases now. "We can't fully evaluate the risks we face," says Stone. "A lot of people won't want to do anything. I think that's unfortunate." Greenhouse warming is a threat that should be taken seriously, say Stone and others toward the skeptical side. Possible harm could be addressed with flexible steps that "evolve as knowledge evolves," says Stone. By all accounts, knowledge will be evolving for decades to come.



Greenhouse warming, hazy cooling. Radiation trapped by today's enhanced greenhouse (left bar) might be nearly counteracted by the still highly uncertain indirect effect of pollutant aerosols.

The challenge for climate researchers—and the accompanying uncertainty—come in three arenas: detecting a warming of the globe, attributing that warming to rising levels of greenhouse gases, and projecting warming into the future. As it happens, new knowledge reported by IPCC clearly narrows the uncertainties inherent in the detection problem and strengthens the link to greenhouse gases, but it leaves projection of future warming more uncertain.

"The detection problem seems to me to be almost solved," says observational climatologist David Gutzler of the University of New Mexico in Albuquerque. The IPCC puts global warming over the 20th century at 0.6° ± 0.2°C, as measured by instruments near Earth's surface. That's a broader range than IPCC reported in 1995, which might suggest increasing uncertainty, but back then, less effort was put into quantifying uncertainty. Now the range is pegged at the 95% confidence level, making it "very likely" the world has warmed, according to the parlance adopted for the first time by IPCC. "The most dramatic difference since '95 is the decrease in the uncertainty" associated with recent warming, says statistical climatologist Michael Mann of the University of Virginia in Charlottesville, who contributed to the report. He credits the increased confidence to more sophisticated and effective statistical techniques for analyzing sparse observations.

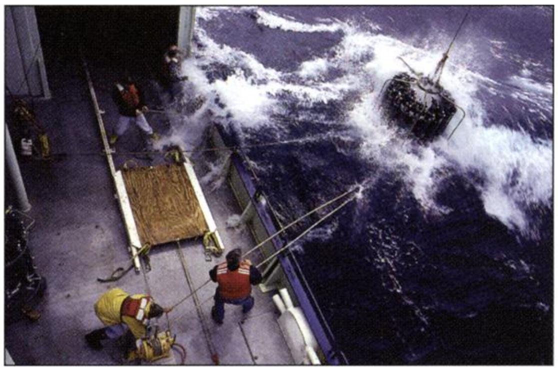
The globe very likely did warm, but "attribution is much harder," notes Gutzler. To pin the warming on increasing levels of greenhouse gases requires distinguishing greenhouse warming from the natural ups and downs of global temperature. In 1995, IPCC found that, despite remaining uncertainties, "the balance of evidence suggests that there is a discernible human influence on global climate." A rather wimpy state-

Greenhouse Warming Passes One More Test

Are humans indeed warming the world? If so, will future warming be big enough to matter? Confident answers depend in large part on the credibility of climate models. Greenhouse critics claim modelers can get any answer they like about warming simply by adjusting any of the numerous inputs whose values in the real world remain uncertain. Climate model running on the warm side? Crank in a bit more pollutant haze to shade the planet and cool it down, they say, and everything will look fine. Modelers have long argued that constraints such as the need to simulate current climate and the history of atmospheric warming keep their models more honest than that. Now a new, independent reality check from the ocean has strengthened their case.

On pages 267 and 270 of this issue, two groups of climate researchers report that two climate models have passed a new test: simulating the warming of the deep oceans during the past half-century. Their success "provides stronger evidence climate is changing," says climate modeler Simon Tett of the Hadley Centre for Climate Prediction and Research in Bracknell, United Kingdom, "and it's likely due to human influence." However, a conflict between the two studies underscores the difficulties in gauging how bad greenhouse warming could be.

Why worry about the ocean, when greenhouse warming of the atmosphere is what life on the surface will have to deal with? "The ocean is the flywheel of the global climate system," explains climate modeler Tim P. Barnett of the Scripps Institution of Oceanography in La Jolla, California. The ocean holds so much heat that it tends to steady the rest of the climate system. "If there's one place you want to get it right, it's there," he says. Last year, oceanographer Sydney Levitus of the National Oceanic and Atmospheric Administration (NOAA) in Silver Spring, Maryland, and his colleagues reported that the top 3000 meters of oceans worldwide had gained 18.2 x 10^{22} joules of heat between 1955 and 1996 (*Science*, 24 March 2000, p. 2126). In their new paper, they calculate that less than a tenth as much heat as that went into warming the global atmosphere and melting sea ice and glaciers. Their conclusion: If you're keeping track of the heat trapped by the strengthening greenhouse, the ocean is almost all that matters.



Deep heating. Measured warming in the ocean matches greenhouse warming predicted by models.

With that pivotal role in mind, both Barnett and Levitus tested greenhouse warming in a climate model against how the ocean has actually warmed. Barnett used the Parallel Climate Model developed at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, and Levitus used the model from NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey. Both groups drove the warming with the increasing greenhouse gases of the past century, and both found that the models' world oceans warmed by just about as much as observed. And it appears that the ocean warming was likely due to increasing greenhouse gases, not the random oscillations of the climate system that modelers call internal variability. "The rising heat content of the past 50 years is way out of the bounds of internal variability" produced in a model, says modeler Thomas Delworth of GFDL, a co-author of the Levitus paper. The warming in the model ocean so closely matched the strength and geographical distribution of the actual warming that Barnett calculated with confidence exceeding 95% that human-produced greenhouse gases are behind real-world warming.

While the results of the two models further support the emerging consensus that humans are warming the world (see main text), they also drive home problems with making predictions from models. Just how bad warming will get by the end of the century, say, will depend on how much greenhouse gas—principally carbon dioxide—enters the atmosphere and how strongly the climate system reacts to it, a property called climate sensitivity. For more than 20 years, researchers have been estimating that climate sensitivity to a doubling of carbon dioxide is between a modest 1.5°C warming and a searing 4.5°C. Indeed, the NCAR and GFDL models reflect that recalcitrant uncertainty in their climate sensitivities of 2.1°C and 3.4°C, respectively.

How, then, can the two models agree about the past century of ocean warming? The explanation may lie in one of the remaining knobs on the climate machine: aerosols, the microscopic particles of sulfate, soot, and organic crud produced by fossil fuel burning, biomass burning, and volcanoes. Researchers are still figuring out how much aerosol of each sort is up there, how effectively each absorbs solar energy or reflects it back to space, and how each affects the number and size of cloud particles, another potent player in the climate system. The two models assumed different fossil-fuel aerosol histories, and the NCAR model ignored volcanic aerosols—discrepancies that may have compensated for differences in the models' sensitivities. As a result, says climate modeler Myles Allen of the University of Oxford, "both models could be right for the wrong reason." But whichever is more realistic, Allen says, the finding that real-world warming is not likely due to internal variability stands—although clearly, some better informed knob twiddling is still in order. —R.A.K.

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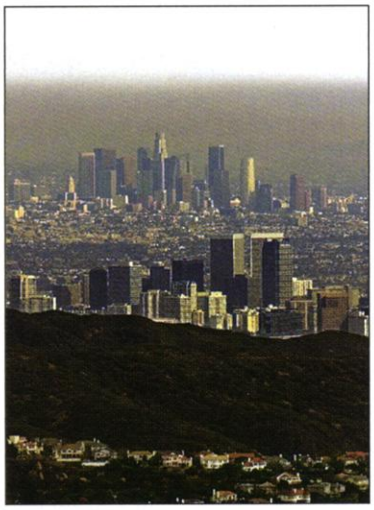
ment, but it was the first positive attribution made by IPCC. This time around, the attribution statement is dramatically beefed up: "... most of the observed warming over the last 50 years is likely [66% to 90% chance] to have been due to the increase in greenhouse gas concentrations."

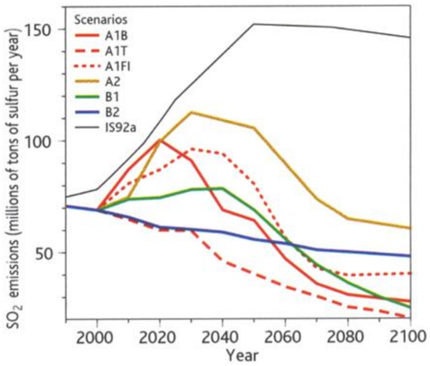
That's stronger than the draft statement leaked last spring (*Science*, 28 April 2000, p. 589), which is fine with modeler Jerry D. Mahlman, who recently retired as director of the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. "I'm quite comfortable with the confidence being expressed," says Mahlman, who was not involved in writing any part of the report. Mahlman cites three developments that increase his confidence. First, it's warmer than it was, even warmer now than in 1995. Second, the current warmth looks extreme, even unique, in the past 1000 years. And third on Mahlman's list is the performance of the climate models.

The report states that confidence in the models has increased. Some of the model climate processes, such as ocean heat transport, are more realistic; some of the models no longer have the fudge factors that artificially steadied background climate (*Science*, 16 May 1997, p. 1041); and some aspects of model simulations, such as El Niño, are more realistically rendered. The improved models are also being driven by more realistic climate forces. A sun subtly varying in brightness and volcanoes spewing sun-shielding debris into the stratosphere are now included whenever models simulate the climate of the past century.

With all the new improvements, the most sophisticated models can now simulate the bumpy rise in global temperature seen in the past 100 years—including the once mysterious rise and temporary plateau at midcentury, now attributed to the cooling effects of aerosols. The models are "getting quite a remarkable agreement" with reality, says modeler John Mitchell of the Hadley Centre for Climate Prediction and Research in Bracknell, United Kingdom, who headed the report's detection and attribution chapter. All of this gives Mahlman and many others confidence that most of the warming is likely due to increasing greenhouse gases.

"That's stretching it a bit," says satellite climatologist John Christy of the University of Alabama, Huntsville, who was an author of the chapter on observed climate change. Stone says a confident attribution to humans "may be right," but "I just know of no objective scientific basis for that." They and others agree that the dramatic 20th century warming, following millennium-long records of a cooler world, has a certain visceral appeal. But they remain cautious about the ability of the models to attribute the warming to greenhouse gases. "I don't know that they reproduce climate any better" than they did 5 years ago, says climate modeler Tim P. Barnett of the Scripps Institution of Oceanography in La Jolla, California. Climate modeler Jeffrey Kiehl of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, agrees that "we have made progress, but sometimes progress means you learn you need to know more."





Brighter outlook? Increasingly foul air (top curve) and its cooling effect is now thought to be a less likely scenario.

For Kiehl, a striking example of increasing uncertainty is the pollutant hazes of aerosol particles from fires of all sorts, from fossil fuel burning to cooking fires. Any model must be told how much aerosol there is and how it will behave—whether it's bright enough to reflect solar energy back to space and cool the planet or dark enough with soot to absorb solar energy and warm Earth. It could also cool the atmosphere indirectly by forming new cloud droplets that would reflect solar energy even better than the aerosol particles.

"The more we learn [about aerosols], the less we know," says Kiehl. That's evident in the body of the IPCC report. It says that the uncertainties are so large that a best estimate with error bars of the indirect cloud effect of aerosols is still impossible. In fact, the report increases the range of possible aerosol cloud effects over 1995 estimates. Now they span from no effect to a cooling large enough to almost compensate for the total warming from all current greenhouse gases.

In addition to uncertainties about what to put into models, many researchers see looming—and frustratingly recalcitrant—uncertainties in the way models respond to inputs. "The uncertainties are large—as large as 20 years ago," says Texas A&M's North. The traditional measure of model uncertainty is the range of climate sensitivity, defined as the amount the atmosphere would warm if atmospheric carbon dioxide doubled. The first official look at the greenhouse problem, a 1979 U.S. National Research Council study headed by the late Jule Charney, concluded that a carbon dioxide doubling—which is expected by the end of the century—might warm the world as little as a modest 1.5°C or as much as a disastrous 4.5°C. The 1.5° to 4.5°C range of climate sensitivity has been repeated unchanged in four IPCC reports now—it's like Planck's constant, quips one modeler, unchanging with time.

An unchanging climate sensitivity and its implied lack of progress bother most researchers. Mahlman puts the best face on it by arguing that although the range hasn't changed, the chance that the real sensitivity falls somewhere in that range has increased over the years, from 2 in 3 in 1979 to perhaps 9 in 10 today. North, although able to go along with the IPCC's statement attributing 20th century warming to greenhouse gases, sees the "huge range of climate uncertainty among the models" as a sign of fundamental problems. "There are so many adjustables in the models," he says, "and there is a limited amount of observational data, so we can always bring the models into agreement with the data." Models with sensitivities to CO_2 inputs at either extreme of the range can still simulate the warming of the 20th century, he notes, suggesting that adjustables like aerosols and clouds are compensating for the sensitivity differences.

The uncertainties give some researchers pause when IPCC so confidently attributes past warming to the greenhouse, but projecting warming into the future gives almost everybody the willies. When the IPCC report came out in January and the headlines trumpeted the prospects for a scorching fin de siècle, climate researchers were instead struck by the growing recognition of uncertainties. There was not only the unchanging climate sensitivity, but also a growing realization that where humans are involved, prediction gets even harder. The near doubling of the range of possible warming is due largely to expectations that, rather than fouling the air more and more, countries will likely clean up their acts, reducing aerosol emissions and the compensating cooling they would have produced. This is all well and good, but "social uncertainty is hard to discuss," says Mahlman, "because we don't have a clue how people are going to react 30 years from now. The scientific problem you evaluate, the social problem you just handwave." Witness President George W. Bush's derailing of U.S. participation in the Kyoto Protocol for controlling greenhouse gas emissions.

What policy changes would researchers who struggle daily to understand the climate system recommend in the face of this cascade of uncertainties? Most see cause for concern about warming, despite all the doubts. "A number of uncertainties are still with us," says Kiehl, "but no matter what model you look at, all are producing significant warming beyond anything we've seen for 1000 years. It's a projection that needs to be taken seriously." Modeler Linda Mearns of NCAR would emphasize a goal of identifying all the uncertainties rather than quickly narrowing the known ones, but "there's no evidence the problem will go away. It's clear there's still great concern about the future." Even Washington's Charlson, who chides IPCC for not addressing "big scientific uncertainties," concludes that because "the evidence for chemical change of the atmosphere is so overwhelming, we should do something about it."

–RICHARD A. KERR

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