

CLIMATE MODELERS STRUGGLE TO UNDERSTAND GLOBAL WARMING

In the sweltering summer of 1988 the public heard claims that global warming from the greenhouse effect had definitely begun. In the chilly winter of 1989/90 they are hearing skeptics question whether it will ever arrive. Just as temperatures fluctuate about an average value, the mean opinion on global warming falls somewhere between these extremes.

To narrow this range of uncertainties surrounding the greenhouse effect, researchers have been working for decades to simulate the highly complex and imperfectly understood atmosphere with sophisticated, three-dimensional models. They face a herculean task, with high stakes riding on their predictions. Currently the climate models estimate that a doubling of atmospheric carbon dioxide (expected in the next century) may raise global temperatures somewhere between 1.5 and 4.5 K.¹

Skeptics have long questioned whether such model predictions are sufficiently accurate to serve as guides to making policy, and some have suggested—only qualitatively so far—factors that might keep the temperatures from rising. The climate modelers stand by their predictions that increased releases of infrared absorbers such as carbon dioxide will warm Earth's climate. They have much less confidence in the models' abilities to answer definitively by how much and by when. Nor can they reliably predict what the regional climate will be.

Additional data on Earth's climate are now being gathered by the three satellites that constitute the Earth Radiation Budget Experiment. Recently these data provided evidence that increases in temperature are amplified, as predicted, by positive feedback from water vapor. Other recent studies have shown the importance of the feedback between clouds and climate, which is now poorly understood.

The greenhouse effect that the models are attempting to gauge results from atmospheric constituents that are generally transparent to short-

wavelength radiation but strongly absorb long-wavelength radiation. (See the article by Veerabhadran Ramanathan, Bruce R. Barkstrom and Edwin F. Harrison in *PHYSICS TODAY*, May 1989, page 22.) These constituents allow solar radiation to penetrate to Earth's surface but trap the reradiated infrared. The greenhouse gases in turn emit infrared radiation. The additional infrared absorbers decrease the fraction of surface-emitted radiation that escapes to space. But the radiation to space must remain constant if Earth is at equilibrium, so the surface temperature warms as the fraction radiated to space decreases.

Water vapor is the most potent greenhouse gas, and together with CO₂, it is largely responsible for keeping our planet at the comfortable 15°C average temperature rather than at the chilly -18°C that would obtain without an atmosphere. However, concern focuses on carbon dioxide because its atmospheric concentration (less than 10% that of water vapor) is increasing, and hence it may be shifting the current equilibrium. Some trace gases, such as methane, chlorofluorocarbons and nitrous oxide, have concentrations about 100 times smaller than that for CO₂, but they are growing more rapidly. Simulations of the impact of a doubling of CO₂ can also represent some radiatively equivalent mixture of CO₂ and other greenhouse gases.

A doubling of CO₂ would increase the atmospheric trapping of long wavelength radiation by about 4 W/m² compared to the trapping of about 150 W/m² in today's atmosphere. This small change may be amplified or dampened by a variety of feedbacks.

Water-vapor feedback

Climate models have long included a positive feedback from water vapor: As increasing temperatures on Earth's surface evaporate more water, the additional water vapor increases the greenhouse effect, elevating the temperatures still further.

Because of this effect, the temperature rise from an increase in CO₂ may be 1.5 to 3 times larger than it would be without the feedback. Although the water-vapor feedback is firmly rooted in theory, only recently has there been physical evidence for it: Ameet Raval (University of Chicago) and Ramanathan combined ERBE satellite data with surface-temperature readings from the National Meteorological Center data set to find correlations among water vapor, temperature and trapped radiation.² The data provide significant confirmation of a major aspect of the models.

Raval and Ramanathan define the greenhouse effect G as the difference between the thermal radiation emitted by the oceans and the thermal radiation leaving the top of the atmosphere. They attempt to eliminate the temperature dependence of G by defining a normalized greenhouse effect g as $G/\sigma T^4$, where σ is the Stefan-Boltzmann constant and T is the temperature.

The case for a positive water-vapor feedback rests on three pieces of evidence. First Raval and Ramanathan found that the normalized greenhouse effect increases linearly with temperature: While the temperature variation in the data is spatial, they imply a similar effect with temporal variations. (See the figure on page 18.) The Chicago pair argue that the change of g with temperature must come primarily from an increased concentration of absorbers, namely water vapor. Next they show that the logarithm of the water-vapor concentration, which is determined from microwave satellite soundings, varies linearly with surface temperature. This is just the dependence—both qualitatively and quantitatively—that one would calculate from the Clausius-Clapeyron equation governing the saturation vapor pressure. Finally the two researchers show that g increases logarithmically with the water-vapor concentration. They have performed this analysis only for regions of clear sky, although the ERBE satellites record

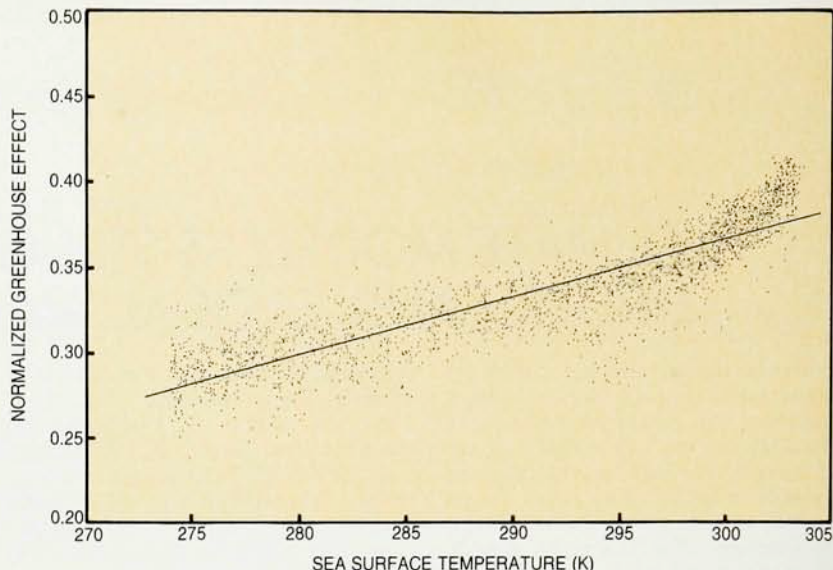
data for both clear and cloudy skies. However, Ramanathan says that inclusion of cloudy regions does not necessarily alter their conclusions.

A few atmospheric scientists contend that the water-vapor feedback can be negative rather than positive in regions such as the intertropical convergence zone (near the equator), where warm, moist air drives a strong convective circulation. Water vapor formed by evaporation from the surface carries its heat in narrow towers of rapidly rising air to the upper troposphere, where it releases heat as it condenses and precipitates. The upwelling moist air from below is then replaced by dryer, downwelling air. Hugh Ellsaesser (guest scientist at Lawrence Livermore National Laboratory) has stressed the importance of this process for a number of years.³ Richard Lindzen (MIT) asserts in an unpublished paper that the net result is a dryer atmosphere above about 5 km. He believes the convection will short-circuit the greenhouse absorption, leading to a negative feedback. Some other atmospheric scientists will not be convinced, however, until they see quantitative, self-consistent calculations of the effect. They note that current observations do not support Lindzen's assertions. Raval and Ramanathan argue that the ERBE data, which integrates the absorption at all altitudes, including the upper troposphere, indicates that the greenhouse effect is, if anything, stronger in the more highly convective regions. There is a slight dip in the greenhouse effect at temperatures corresponding to the subtropics (290–298 K), but Ramanathan asserts that the linear relation between water vapor and temperature still dominates.

Cloud feedback

Whereas the water-vapor feedback is considered well understood, other feedbacks are so poorly understood that their very sign is in doubt. The cloud-climate interaction is the source of the largest uncertainty in climate models. Clouds tend to cool the Earth because they reflect incoming sunlight; they also tend to warm the Earth because they trap the infrared radiation. ERBE data indicate that the net result of these opposing tendencies is to cool the planet. But will this cooling by clouds increase or decrease as more greenhouse gases burden the atmosphere?

Last year Robert Cess (State University of New York, Stony Brook) led an effort⁴ to find how much the various climate models differed with respect to their handling of clouds. Researchers associated with 14 differ-



The greenhouse effect shown here is the difference between thermal radiation emitted at Earth's surface and the radiation leaving the top of the atmosphere, normalized by the infrared emission. The temperature variation is evidence that increased surface evaporation from rising temperatures will further amplify any warming. (Adapted from ref. 2.)

ent general circulation models agreed to run their models under similar circumstances and to measure a climate-sensitivity parameter, defined as the change in temperature with a change in the greenhouse forcing. The sensitivity parameters measured for clear-sky conditions agreed extremely well, indicating high consistency among the models. However the sensitivity parameters for both clear and cloudy skies varied by a factor of nearly three, and ranged from weakly negative to strongly positive.

Cess notes that many other factors, held constant in this particular sensitivity test, can further influence the cloud-climate interactions. In recent work, Cess has used the ERBE data given in reference 5 to examine cloud properties and found that they vary with the seasons. These data may aid research on the interactions between clouds and climate.

John F. B. Mitchell, Catherine A. Senior and William J. Ingram of the British Meteorological Office, Bracknell have found further evidence for the sensitivity of circulation models to cloud properties.⁶ The three researchers started with a model that predicts a global temperature increase of 5.2 C for a doubling of CO₂. When they altered the representation of clouds in the model, the temperature response was reduced to 2.7 K. In this simulation, as the temperature rose in response to enhanced CO₂,

water clouds replaced ice clouds near the freezing level, and the predicted temperature increase fell to 1.9 C.

Temperature trends

Besides gazing into the future through a screen of computer graphics, climatologists try to peer into the past through historical temperature records. Two questions impel the search: Has the planet become warmer over the past 100 years as CO₂ concentrations have risen from preindustrial levels of 280 ppm to the current values, which exceed 350 ppm? Can the climate models reproduce the observed change? Again large uncertainties characterize the answers.

Cataloguing temperatures over the globe has been far from systematic. Instruments and techniques have varied with time and with location. Recording stations have changed locations, or the nature of the locations surrounding the stations has changed. Many of these factors average out when large numbers of stations are examined over long time periods. But one troublesome systematic effect will not average out: the tendency of stations near burgeoning cities to register increased temperatures associated with the urban heat islands. Most analysts correct for this heat-island effect in some way, but they still estimate that it may exaggerate the temperature rise over the past 100 years by about 0.1 K.

Sets of land data of course represent the temperatures for only about one third of Earth's surface. Marine-air and sea-surface temperature readings have also been collected during the past century, but they, too, are awash in uncertainties. The ships reporting these data sample only a small portion of the oceans that fall along standard routes. Historically the thermometer was placed in a bucket of water hoisted from the sea, and evaporation from the bucket would cool the water before its temperature was assessed. Analysts from the University of East Anglia, England and from the British Meteorological Office have tried to correct for these data, accounting for differences in evaporation for wooden and canvas buckets.⁷ (Seamen today often measure temperatures at the intake for cooling water.)

Using a data set that combines land and marine temperatures, Phil D. Jones, Tom Wigley and Peter B. Wright (University of East Anglia) estimated⁸ that Earth is now 0.5 K warmer than in the mid 1880s. James Hansen and Sergej Lebedeff of the NASA Goddard Institute for Space Studies, New York⁹ placed the past warming at 0.6 ± 0.2 K, based on a similar data set for land only.

Based on his temperature observations and studies with a GISS climate model, Hansen in 1988 stated to Congress that "the global warming is now sufficiently large that we can ascribe with a high degree of confidence a cause and effect relationship to the greenhouse effect..." As if to temper this air of certainty, Kirby Hanson, George Maul and Thomas Karl (National Oceanic and Atmospheric Administration) soon afterward published their study of climate within the contiguous U. S. over a period dating back to 1895, which indicates no overall trend in either temperature or precipitation.¹⁰ Subsequently another group reported¹¹ that the temperature changes for the contiguous 48 states represented a warming rate of 0.26 K/century. Even the null result for the U.S., which covers only about 1-2% of the globe, does not necessarily contradict the estimates of worldwide temperature increases: Temperature changes do not occur uniformly over the globe.

A prevailing consensus is that Earth may have warmed by about 0.5 K in the last century—a weak signal that is not much larger than the interannual fluctuations. Current climate models have so far only simulated the temperature increase expected for a doubling of CO₂ but these results can roughly indicate what the tempera-

ture increase might have been over the past 100 years, when the CO₂ increase was only 25%. Models that predict warmings of 2 K or 3 K for a CO₂ doubling correspond to temperature increases of 0.5 K and 0.7 K, respectively, for the past century. The thermal inertia of the oceans causes the temperature response to lag behind the CO₂ forcing by some time interval which is not precisely known.

The models should not be asked to account entirely for the past climate changes because they do not include many factors besides the greenhouse gases that influence the climate. Volcanos and variations in the solar radiation certainly are among these factors. So are industrial emissions of sulfur dioxides that may alter the albedo. Wigley has estimated that the upper limit on this effect is sufficiently large that it may have significantly offset the temperature changes that have resulted from the greenhouse effect.¹²

Assessing the models

A recent review from the George C. Marshall Institute on the current state of knowledge about the greenhouse effect is being widely circulated among policy makers. The report suggests that variations in the solar flux of 0.3 to 0.5%, together with other natural variables, might account for the observed warming. The solar flux during the last sunspot cycle did not vary by more than 0.1%, but the Marshall report points out that the flux of some stars that are similar to the sun varies by 0.4%. Some disagree with this explanation of temperature change. Martin Hoffert (New York University) said there is no basis to assume that the variations in the sun's flux would change from one cycle to another when the data shown in the Marshall report show no evidence of such cycle-to-cycle variations in other stars. Wigley points out that a 0.5% deviation in solar flux would correspond to a forcing of only about half that due to the increases in greenhouse gases over the past century. If the solar forcing has a measurable effect on climate, then the greenhouse gases must have an even larger impact. The Marshall Report concluded that a prudent investment in resources such as supercomputers would yield usefully reliable answers in only 3 to 5 years. Syukuro Manabe (NOAA's Geophysical Fluid Dynamics Lab), who led the development of one of the most complete climate models, believes the current models are at a higher and more useful state of development than the report states, but he

feels that substantial advances in the models will require more than 3 to 5 years.

Jerry Mahlman, director of GFDL, defends the global circulation models as central tools, which are attempting one of the most difficult calculations ever undertaken. He points to successes in simulating the very cold climate of the last glacial maximum and of the extreme temperatures found on Mars and Venus. Among the predictions to which he would assign a probability of greater than 90% are global mean surface warming, large stratospheric cooling, global-mean precipitation increase and enhanced winter surface warming in the northern polar regions. To address the significant deficiencies that still remain, he admits the need for more data, more computer time or speed (which can translate into finer grid spacing and better physics for the models) and more scientific talent.

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