Is the Greenhouse Here?

A global warming plus hints of other climatic changes are starting to build the case for an intensifying greenhouse, but can the case be proven in time?

PROVING that increasing concentrations of carbon dioxide and other trace gases in the atmosphere are altering Earth's climate is years if not decades away. But, having recently agreed that Earth has warmed slightly during the past century, researchers are beginning to find hints of other climatic changes that should accompany a global warming induced by carbon dioxide.

Such an ensemble of climate changes is just what researchers are now counting on to distinguish as soon as possible between the greenhouse and natural variations. No one type of change is likely to convince the scientific community of the reality of the greenhouse effect or its true magnitude until well into the next century, when the world could be condemned to dramatic changes. The best bet for early detection seems to be the identification of a number of changes—warmer weather, warmer ocean water, a cooler stratosphere, and increased precipitation, for example—that together would, in all likelihood, be caused by a greenhouse.

The approach now being pursued is more like developing a composite picture of a culprit rather than arresting the first suspect who has the same color eyes. Researchers call the technique fingerprinting, although it is hardly as conclusive as the human technique. And they are beginning to scrutinize what may be the first components, albeit fuzzy ones, of the greenhouse fingerprint.

The one component of the fingerprint that almost everyone now agrees on is the current global warming. The world is clearly warmer now than it was a century ago. According to a compilation made by Philip Jones, Tom M. L. Wigley, and Peter Wright of the University of East Anglia that includes hundreds of millions of temperature observations, the surface of the globe warmed about 0.5°C between 1861 and 1984. This warming is, as scientists like to say, consistent with computer simulations of the effects of increasing carbon dioxide.

But here enters the first of many uncertainties. Computer models predict a warming by now of anywhere from 0.3 to 1.1°C, depending on the initial carbon dioxide concentration, the ability of the ocean to slow the warming by absorbing heat, and the sensitivity of Earth's climate system to carbon dioxide, rather than the models'. If one includes the uncertainties inherent in the increasing amounts of other greenhouse gases such as methane and chlorofluorocarbons, whose effects could eventually double those of carbon dioxide, the consistency of one type of observation with prediction is not so impressive.

There are still more limitations that discourage most researchers from drawing any conclusion from the surface temperature record alone. The half-degree warming itself suffers from uncertainties that all climate observations share. Geographic coverage is uneven now and was worse in the past. Instruments and techniques change. The warmth of urban centers has encroached on once-pristine observing sites.

The world is about half a degree warmer now than it was a century ago. Is that the greenhouse?

In addition, good records seem never to be quite long enough to sort out with any certainty natural variations from a greenhouse effect. The East Anglia global record of surface temperature goes back 130 years, for example, but at that time the Little Ice Age, a seemingly global chilling of uncertain origin, had only just ended. And it appears to have been warmer in medieval times, before the Little Ice Age, than now. Is the current warming simply a natural recovery?

Because the prospects are poor for understanding the cause of the Little Ice Age, not to mention the decades-long pauses in the warming and even coolings seen since then, climatologists are looking for help from other kinds of records. Next to surface temperature, the temperature of the lower stratosphere has been most extensively analyzed. As carbon dioxide doubles throughout the atmosphere, radiative emissions to space by stratospheric carbon dioxide should cool those altitudes by as much as 10°C while the surface temperature increases by no more than about 4°C, according to model predictions. Detection of such a large stratospheric warming would say little about the much-debated magnitude of the warming near the surface, but it would reassure researchers that at least some aspects of their models could be found in the real world.

Most searches for a cooling in the lower stratosphere, where balloon-borne radiosondes can reach, have been negative by strict statistical standards. The record is only about 25 years long, there is considerable natural variability of temperature, and coverage is far from complete. But even some statistically negative searches show a cooling in the lower stratosphere that is greater at higher latitudes, as predicted.

A few recent searches, however, have uncovered significant stratospheric coolings. Karen Labitzke of the Free University of Berlin and her colleagues took unusual care in developing monthly mean temperatures from an exceptionally large data base. For 10° latitude bands at mid-latitudes, means are based on about 3000 observations each. Averaged between 20°N and 70°N, the lower stratosphere cooled at a rate of 0.34°C from 1966 to 1980. That cooling rate is significant, Labitzke and her colleagues believe, and they calculate that it is consistent with that expected from increasing carbon dioxide.

In the Southern Hemisphere, radiosonde coverage is much more sparse, but David Karoly of Monash University in Clayton, Australia, has found a significant cooling there in the lower stratosphere above selected stations. All but 2 of 19 stations have cooling trends from 1964 to 1985 ranging from 0.2 to 1.0° per decade. At only five of the stations is the trend statistically significant at the 95% level, but Karoly enhanced the greenhouse signal by contrasting the cooling in the lower stratosphere with the warming in the troposphere below. His index of this temperature difference showed a positive trend—the expected greenhouse signal—at all 19 stations, 13 of the trends being significant.

The 20-year stratospheric cooling trend that may be emerging from the climatic noise may also be marginally detectable during this decade, even though debris from the 1982 eruption of El Chichón absorbed solar radiation and temporarily warmed the lower stratosphere. Mark Schoeberl of the Goddard Space Flight Center in Greenbelt, Maryland, has coordinated a group of stratospheric specialists in a review of some temperature trend studies.

This group concludes that the global lower stratosphere cooled about 0.5° ± 0.5° between 1979 and 1985. In the upper stratosphere, where the carbon dioxide effect should be accentuated, the cooling appears to have been 1.5° to 2°C, based on satellite and rocket observations.

Unfortunately for those looking for a greenhouse signal, other forces can cool the stratosphere. Decreasing solar activity since 1980 certainly has. And any decrease in ozone induced by increasing concentrations of chlorofluorocarbons will itself induce a cooling, at least in the upper stratosphere. It could be as large as that due to carbon dioxide. The situation may be particularly complicated in the Southern Hemisphere where the springtime Antarctic ozone hole may have some influence.

Computer models predict a number of other greenhouse signals, but no global searches for them have been attempted. The scarcity of observations does not allow them as yet. However, several regional, often preliminary studies have recently revealed greenhouse-like trends.

According to the models, the hydrologic cycle of evaporation and precipitation should run faster overall under increased carbon dioxide. However, the increased precipitation would not necessarily fall evenly over the hemisphere. The models tend to agree that precipitation would increase poleward of a latitude of about 30° and within 5° of the equator. Between those zones, the models are more variable but tend to call for a decrease.

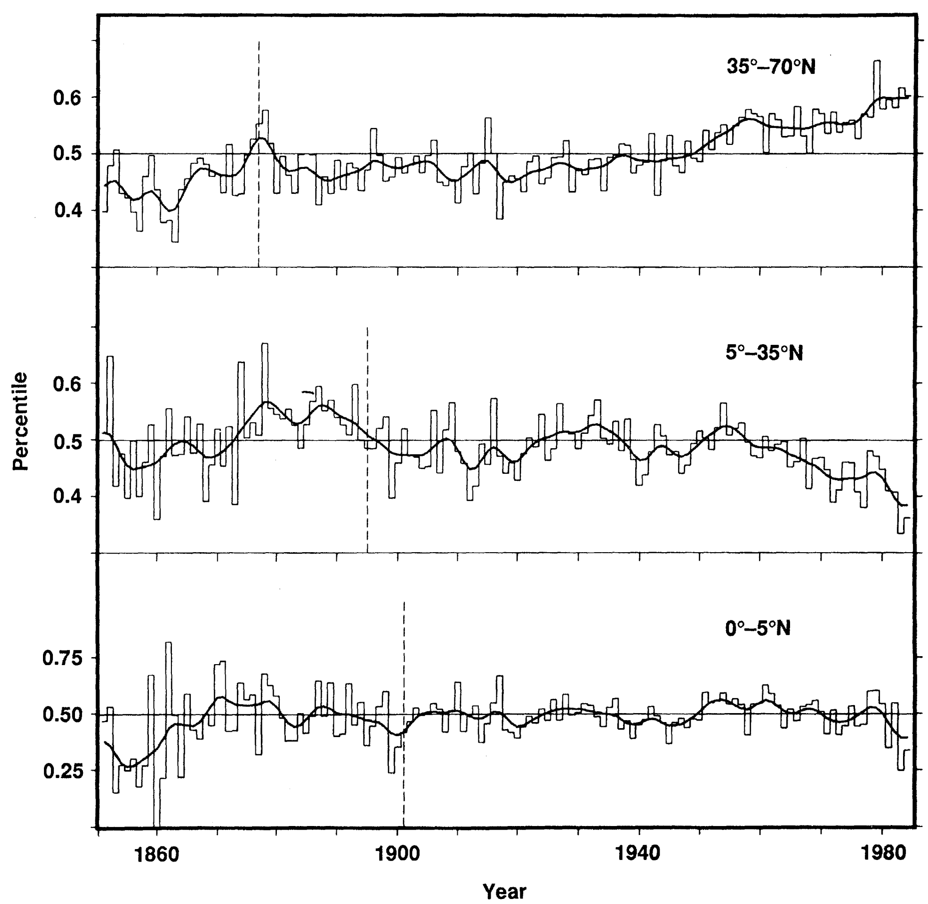
Raymond Bradley of the University of Massachusetts and his colleagues reported that in their record of Northern Hemisphere precipitation over land since 1850, precipitation remained fairly steady since before the turn of the century until about 1940. Then it began rising in the zone between 35° and 70°N and falling between 5° and 35°N but remained steady within 5° of the equator, where data coverage is generally poor. Bradley and his colleagues note the similarity of the observed and predicted patterns, but they caution, as do most researchers in this line of work, that similarity does not imply a causal link.

Along these same lines, P. Krahe, Hermann Flohn, and A. Hense at the University of Bonn have found a "remarkable" increase in the amount of water vapor over the Indo-Pacific region during the past 20 years. At all five of the selected radiosonde stations within 10° of the equator, the temperature has risen about 0.05°C per year. Each warming trend is statistically significant at the 95% level. At four of the five stations, total water and relative humidity have increased dramatically between altitudes of 3 and 6 kilometers, rising 10 to 20% and more in absolute terms. Seven out of eight of these trends were significant.

Closer to home, Thomas Karl of the National Climate Data Center in Asheville and George Kukla and Joyce Gavin of the Lamont-Doherty Geological Observatory have found a drastic decrease in the daily range of temperature found at sites across the United States. In a record of daily highs and lows for individual sites extending back to 1900, they found nothing but modest fluctuations until the 1940s, when the mean diurnal range began to narrow. During the past 10 to 15 years, the decrease has accelerated to the point that it totals about 1°C.

A decrease in the diurnal range is another of the predicted greenhouse effects. A greenhouse warming would increase evaporation and thus the amount of water vapor. Additional water vapor would block more radiation that would otherwise escape from near the surface during the night, which would raise the minimum temperature. More water vapor also might increase cloudiness, decreasing radiation at the surface during the day and lowering the maximum.

Although a number of intriguing candidates are appearing that might be part of a fingerprint, no one is claiming a certain identification of the greenhouse signal. The tentativeness of the situation was recently driven home when Tim P. Barnett of Scripps Institution of Oceanography and Michael Schlesinger of Oregon State University made an objective comparison between the models' behavior of a greenhouse signal around the globe and the way it actually has behaved. They tested surface temperature since 1899 and temperature of the troposphere (between the surface and the stratosphere), atmospheric pressure at sea level, and sea surface temperature during the past 25 to 35 years. All four records failed the test. The test of the record of



Computer models call for a wetter world once carbon dioxide has doubled. According to this record of precipitation over the land of the Northern Hemisphere, the weather has become wetter in middle latitudes and drier in low latitudes, as predicted, but remained unchanged near the equator. [*R. S. Bradley* et al., Science **237**, *171 (1987)*.]

surface temperature did show a significant result, but only by dint of opposing 15-year extremes at either end of the record.

Barnett and Schlesinger do suggest that some parts of the greenhouse fingerprint will be more useful than others. In some cases, they say, natural variability could easily mimic the greenhouse signal, especially if the signal is a weak one. The pattern of atmospheric temperature variability, for example, resembles that of the temperature greenhouse signal. But sea surface temperature has a patchy pattern of natural variability and is expected to increase rather uniformly under the greenhouse.

Barnett and Schlesinger's results do not deny that there has been a global warming this century. They simply show that the variation in warming from place to place does not match the pattern predicted by the models very well. Unfortunately, the fault may lie in the warming or in the models. As Hugh Ellsaesser and his colleagues at Lawrence Livermore Laboratory have pointed out, surface temperature changes on time scales of decades to many millennia have always had a patchy pattern. But the models call for a steady pattern of warming symmetric about the equator. That suggests to the Livermore group "that our climate models are inadequate or that there is a fundamental difference in character between climate changes of the past" and those of the future.

Alternatively, present models may be adequate for what has been asked of them so far—the calculation of conditions once the climate system has adjusted throughout to a doubling of carbon dioxide. But early detection requires knowledge of conditions as different parts of the system respond at different rates to increasing carbon dioxide. As Stephen Schneider and Starley Thompson of the National Center for Atmospheric Research in Boulder have suggested, the climate halfway to a carbon dioxide doubling may not look much like the final, equilibrium climate, as assumed by Barnett and Schlesinger. So far, climatologists do not have the months and years of supercomputer time they need to model accurately the current transition to equilibrium.

Fingerprinting is only just getting under way, but the chase is on. Both the subtle clues and the visage of the culprit itself await refinement. ■ RICHARD A. KERR

ADDITIONAL READING

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Molecular Clocks Turn a Quarter Century

It is now 25 years since Linus Pauling and Emile Zuckerkandl proposed the molecular evolutionary clock hypothesis, and a controversial quarter century it has been. Counterintuitive in the sense that anything in evolution might "tick" in a regular manner, the notion of and evidence for a molecular clock nevertheless persists and has become even more pervasive than originally conceived.

Some of the controversy derives from theoretical and experimental considerations of the fixation of DNA mutations. And some derives from clashes over the implication of specific molecular clock results when compared with classical morphological interpretations—the arena of human/ape evolutionary patterns is most notorious here. Nevertheless, molecular clock information is emerging as a potentially powerful tool in reconstructing evolutionary trees (phylogenies) among a wide range of organisms.

To mark the molecular evolutionary clock's quarter century the Journal of Molecular Evolution *recently devoted an entire issue to the subject. Articles touch on clock theory, molecular and whole genome phenomena that could cause deviations from metronomic ticking, and applications of the approach to specific cases. A selection is presented here.*

Origins and Evolution of the Molecular Clock

Emile Zuckerkandl describes how he joined Linus Pauling at the California Institute of Technology in 1959 and began working on the evolution of primate hemoglobin. The notion of a degree of regularity in protein evolution that might provide the basis of a molecular clock developed during the next half dozen years.

"In June 1960," writes Zuckerkandl, "I assumed that numbers of differences in sequence between homologous polypeptide chains could be expressed as the approximate evolutionary time since divergence." This, he says, was "a conceptual jump," the birth of the clock hypothesis.

However, that conceptual jump faced a formidable conceptual barrier—and still does in many ways—namely an antithesis of associating the idea of any kind of regularity with the process of evolution, and for good reason. "Twenty-five years ago," remembers Zuckerkandl, "the diversity of rates in morphological evolution was the strongest argument, in the minds of biologists, against seriously considering the possibility that graded differences between informational macromolecules might be proportional to evolutionary time."

In other words, biologists knew that morphology changed in fits and starts through evolutionary time, so why should macromolecules be any different? It was soon demonstrated, of course, that molecular and morphological changes were not linked in lockstep: a single base substitution in DNA might produce small morphological change, large morphological change, or no change at all, depending on where the substitution occurred. And the notion of neutral evolution began to emerge too, a useful, but not essential, support for the clock notion.

"It became clear early on that the rate at which the clock ticked differed not only between different informational macromolecules, notably between different sectors of DNA, but also between different parts of such molecules, in fact from molecular site to molecular site," says Zuckerkandl. This variability was evident first in sequence comparisons carried out by Zuckerkandl among hemoglobin molecules and by Emmanuel Margoliash on cytochrome c's. Later Margoliash and Walter Fitch constructed extensive evolutionary trees using cytochrome c sequence information.

A complex set of factors combines to make the chance and consequence of change at one nucleotide position different from that at another. As a result macromolecules offer a quasi-clock based on stochastic changes, not a perfect metronomic clock.

Three major issues must be addressed, says Zuckerkandl: "1) Evolutionary clocks have been explored for different compartments of genomes. Where should one look for the best clock? 2) It is now widely considered that most substitutions, even in coding nucleotides, are functionally neutral. Is this legitimate? 3) Are there other biological evolutionary clocks and, if so, is there a common foundation for all biological evolutionary clocks?

Of Apes, Men, and Statistical Analysis

No roundup of current ideas about molecular clocks would be complete without a