Is the Geological Past a Key to the (Near) Future?

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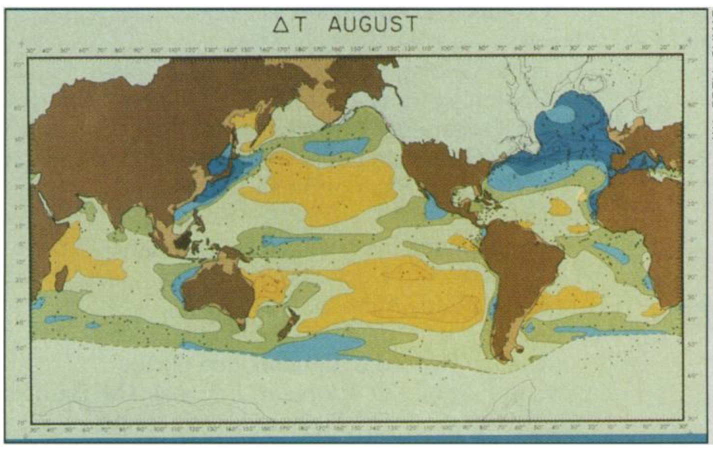
Ever since Leonardo da Vinci unearthed beds of fossil marine shells in the Tuscan hills, the record of the past has been challenging conventional theories of climate. Sages of da Vinci's day had a proper explanation for the shells: The clams and snails had drifted into the hills with the waters of the Biblical Flood. But da Vinci didn't think the climatic event chronicled in Genesis could explain the evidence. How, he wondered, could these largely sedentary mollusks have traveled so far in merely 40 days? He concluded that the received wisdom was wrong: The marine organisms had lived and died in a vanished sea, just where he found them. But, perhaps fearing papal displeasure, he never published his conclusions.

Five centuries later, scientists interested in comparing climatological theories with the tangible record need not be so concerned about unfavorable peer review. Indeed, the threat of greenhouse warming has made the dusty geological record a best-seller in scientific circles. The daunting task of predicting future climate has fallen chiefly on the shoulders of climate modelers, who incorporate thousands of differential equations into their supercomputer creations. But even the very best climate models are full of uncertainties, and their predictions often contradict each other. To develop simulations that can be trusted, modelers are turning to the past: to gases trapped in ice, to pollen grains, to isotopic clues in tiny fossils—to anything, in fact, that can help them confirm, criticize, or otherwise enhance their mathematical constructs.

The search for these benchmarks, says Martin Hoffert of New York University (NYU), has turned paleoclimatology into "an applied science." Yet with this new appreciation of the past come additional doubts. The bare outlines of ancient climates are hard to read, and even apparently robust data can be at odds with researchers' best understanding of how climate works. When geological data and models disagree, climatologists must ask which is wrong. Thus they seek to walk a fine line, hoping data from the past will improve the models—and vice versa—without putting ultimate faith in either one.

Using the past in this way has fans and critics, some success stories—and some stubborn failures. Advocates point to a few cases in which the past has given a clear endorsement to current ideas on climatic processes. For example, cyclical variations in Earth's orbit and orientation toward the sun are thought to be one key driver of climatic history, especially during the past few million years. Collectively called the Milankovitch cycles, for the astronomer who suggested that they might affect climate, these variations can change the intensity of the seasons in each hemisphere. Today, Earth's orbit carries it closest to the sun in January and farthest away in June. That pattern should be giving the Northern Hemisphere slightly warmer winters and cooler summers than it had, say, 11,000 years ago, when Earth was at its farthest from the sun in January.

When an interdisciplinary paleoclimatic research group called COHMAP tested that picture by feeding the orbital parameters for 6000 to 12,000 years ago into climate models, the models showed the expected cooler winters and warmer summers in the Northern Hemisphere. In the northern tropical areas of Africa and Asia, the models also predicted that this enhanced seasonality would intensify the temperature contrast between land and sea, triggering stronger summer monsoons and higher lake levels in the region that is now the Sahara Desert. And this very constellation of effects, including higher lake levels in the Sahara, turns up in the geological record. Orbital variations, it seems, do account for at least some features of an ancient climate. Such confirmation is "very encouraging," says COHMAP leader John Kutzbach of the University of Wisconsin. "At least we understand something about how this one forcing factor works."



W.L. PRELL, CLIMAP

Paradoxical oceans. At the height of the last ice age 18,000 years ago, the oceans were more than 6 degrees cooler than today at high latitudes *(blue)* but only 1 to 2 degrees cooler near the equator *(green)*.

But these successes don't mean the models are always in accord with the full range of data on recent climate change. For example, the major climatic motif of the past million years has been the cyclical advance and retreat of ice sheets. Most climatologists believe orbital forcing played a role in these cycles, too, probably through a complex filter of feedbacks. But no one knows exactly how, and recent data suggesting that the glacial cycles may not always have been in step with the orbital cycles have muddied the picture even further (*Science*, 9 October 1992, p. 220). Not surprisingly, atmospheric modelers have had little luck in getting their computerized climates to simulate the glacial cycles, although Michael Schlesinger of the University of Illinois at Urbana-Champaign claims a recent, as yet unpublished success; by using two types of models in sequence, he and Mikhail Verbitsky of Yale University were able to "grow" ice sheets in the computer.

Trouble in the tropics. Besides being hard to reproduce, the past sometimes delivers a sharp critique of the models. Take the vexing case of the tropical oceans. When modelers simulate a past climate by changing a climate forcing factor such as carbon dioxide or the amount of sunshine hitting Earth, the predicted temperature doesn't change evenly around the globe. For example, doubling the amount of carbon dioxide in a model climate generally heats the poles more than the equator, but it also drives a certain amount of warming in tropical seas. Lowering the carbon dioxide level generally cools the tropical seas. Not so in the real world: In both warm climates and cold, indicators of tropical sea surface temperatures remain stubbornly within a few degrees of present-day values.

The discrepancy can't be written off simply as lack of data, because it shows up in one of the best-studied periods in Earth's history, the Last Glacial Maximum, 18,000 years ago. In the 1970s scientists mounted a campaign called

Back to the future? Climatologists debate the extent to which warm periods like the Cretaceous *(left side of timeline)*, 140 million to 65 million years ago, can offer clues to future climate change.

CLIMAP (the predecessor of COHMAP) to map the climate of the ice age Earth. To the surprise of many, CLIMAP reported that the tropical sea surface was at most 2 degrees cooler than today's, based on the diversity and abundance of various species of marine organisms called foraminifera. But the finding has held up, borne out by isotopic and other studies in the 1980s. Wallace Broecker of Lamont-Doherty Earth Observatory recalls analyzing isotopic data in hopes of challenging the CLIMAP numbers. "I failed. I couldn't find any way around the isotopes—and to my knowledge, neither has anyone else," he says.

During warm periods like the Cretaceous, 140 million to 65 million years ago, the picture is similar: Isotopic data suggest that tropical oceans were at most only a few degrees warmer than now. Meanwhile, CO_2-driven models predict much more warming. "It's a testable prediction—and we're not seeing it," says paleoclimatologist Thomas J. Crowley of Applied Research Corp. in College Station, Texas. "If we hadn't looked in the geological record, we wouldn't even think this prediction could be wrong."

In Broecker's view, such paradoxes are among the most valuable contributions of paleoclimatic data, because they challenge assumptions—and lead to important modifications of existing theory. For example, the sea-surface-temperature paradox has spurred new thinking about how the atmosphere and ocean carry heat from equator to pole. "This is telling us we're missing something important," says Broecker.

A similar lesson emerges from an era about 10,000 years ago, a few thousand years after the last ice age ended. Having warmed almost to present levels, the temperature of the North Atlantic ocean and the lands around it suddenly sank back into glacial ranges. This event, called the Younger Dryas, may have happened in as few as 40 years and been triggered by a swift change in the circulation of the North Atlantic, which in turn weakened the Gulf Stream. The episode may be symptomatic of a fundamental instability in the climate system: Three similar circulation changes apparently occurred between 15,000 and 10,000 years ago. Ocean models can accommodate these shifts—but without the geological record, no one would have thought the ocean was capable of pulling off such stunts, says Crowley.

Often, though, the record sends mixed signals. That's the case even with tropical temperatures. At the height of the last ice age, for example, just a few hundred kilometers away from the relatively warm oceans, snowlines on tropical mountainsides stretched about a kilometer lower than they do today. Pollen composition also suggests significant land cooling in the tropics. Those findings make modeler James Hansen of the Goddard Institute for Space Studies somewhat suspicious of the CLIMAP data. "There's no way you could have the ocean as warm [as now] and land that much colder," he says. This year a new method for estimating temperature from trace elements in corals supported Hansen's interpretation, suggesting that 10,000 years ago, at least one point in the tropical Pacific was about 5 degrees colder than it is now.

Such ambiguity illustrates the pitfalls of using the past as a testing ground for climate models. Says Broecker of Lamont-Doherty: "This whole concept of taking the climate of the past, with limited information about it, and testing models—trying to prod models to produce what you saw. Is that a test? The whole logic of it escapes me....It's like you have one equation with two unknowns."

But given the limited slice of climate change recorded by human instruments, there's no alternative, says modeler Syukuro Manabe of Princeton University and the National Oceanic and Atmospheric Administration. "You can't avoid using paleoclimate data to test the models. It's a matter of self-confidence, self-respect. How can you trust the models if they can't reproduce what happened?"

Mining the past. Indeed, the wealth of climate change hidden in the geological record has tempted other researchers to employ the past more directly, mining it for detailed information about how climate works. Russian scientists, for example, have used past eras as direct analogues of what the future might bring. Western scientists have not favored this "paleoanalogue" method, but just 2 months ago, NYU's Hoffert and Curt Covey of Lawrence Livermore National Laboratory reported another type of study that pulls information directly from the past: They attempted to use paleoclimatic data to find out how sensitive Earth's temperature is to changes in atmospheric carbon dioxide. This parameter, commonly called the climate sensitivity, is typically evaluated for a doubling of carbon dioxide concentration. And it's something of a Holy Grail for climatologists, because with this number in hand, they might have a better chance of calculating future global warming simply by using the recorded increase in atmospheric carbon dioxide.

The number has proved elusive, however. Climate models show a dismayingly large range of responses to doubled CO_2, ranging from 1.5 to 4.5 degrees Celsius. That span is proving hard to narrow, because no one knows exactly how feedbacks such as changes in clouds might amplify or dampen the CO_2 effect. Paleoclimatic data neatly circumvent that problem, since nature itself took all the relevant feedbacks into account when it responded to past carbon dioxide changes, explains modeler Hansen. So if scientists knew the magnitude of the carbon dioxide shift that presumably helped drive a past climate change, and if they had good data on how the planet responded, they might be able to improve the climate sensitivity estimate.

Hoffert and Covey tried to do just that, using two past time periods, one warmer and one colder than now. For their warm extreme they chose the middle of the Cretaceous period, 100 million years ago, when carbon dioxide is believed to have been much higher than it is today; their cold example was the peak of the last ice age, 18,000 years ago, when CO_2 was about 30% lower than it is today. Besides CO_2, their analysis required estimates of other climatic influences, such as the strength of solar radiation and the earth's reflectivity, or albedo. They also needed temperature data, to document how the earth had responded to these forcing factors.

Except for the carbon dioxide levels of the Last Glacial Maximum, which can be measured in bubbles of ancient air trapped deep in the polar ice caps (see p. 926), all these numbers are uncertain. The temperature estimates, for example, were based on the assortment of fossils and their isotopic makeup in deep-sea sediments—and they came from only a smattering of points around the globe. To convert them into a mean global temperature, Hoffert and Covey borrowed a Russian hypothesis of a "universal equation," which describes how temperature varies with latitude and thus makes sense of isolated data points. The upshot of this analysis was a climate sensitivity of 2.3 degrees Celsius, plus or minus 0.9 degrees.

On the face of it, that's a big improvement over the uncertain results of the theoretical models. But not everyone is persuaded that the nebulous geological data are strong enough to support Hoffert and Covey's conclusions. "It's a laudable effort, but my feeling is we can't actually use the data that way. The uncertainty in the data is as great as the uncertainty in the models," says Crowley. "Premature," says paleoclimatologist Thompson Webb III of Brown University, who believes the Russian equation in particular needs more scrutiny.

Hoffert points out that he and Covey included uncertainties in their analysis. And he thinks the paleoclimatic data deserve more credit than his critics allow. To those who carp about the data, he suggests: Go out and improve it. "These are all researchable questions. If you set up a research program with the objective of determining paleotemperature distribution over the earth over the past 100 million years, you could do it," he says. Indeed, geologists and chemists are already making this effort, developing clever new methods to extract information about temperature, carbon dioxide, and other climate factors from mute fossils and rocks (see story on this page).

Until the past comes into sharper focus, the discipline likely will remain caught between the ambiguity of the historical record and the lack of any other empirical check on the models. But, as in da Vinci's day, there's no doubt that the science of paleoclimatology is well-suited to a role as pesky devil's advocate, poking holes in accepted theories of how climate works. And no matter how loud the grumbling about fuzzy data, no one's likely to give up on the geological record any time soon. For information about how the real planet acts during climate change, the past is the only place to go.

–Elizabeth Culotta

Additional Reading

M. Hoffert and C. Covey, "Deriving Global Climate Sensitivity From Paleoclimate Reconstructions," *Nature* **360**, 573 (1992).

COHMAP Members, "Climatic Changes of the Last 18,000 Years: Observations and Model Simulations," *Science* **241**, 1043 (1988).

J. E. Hansen and A.A. Lacis, "Sun and Dust Versus Greenhouse Gases: An Assessment of Their Relative Roles in Global Climate Change," *Nature* **346**, 713 (1990).

CLIMATE CHANGE

Searching for Clues to Ancient Carbon Dioxide

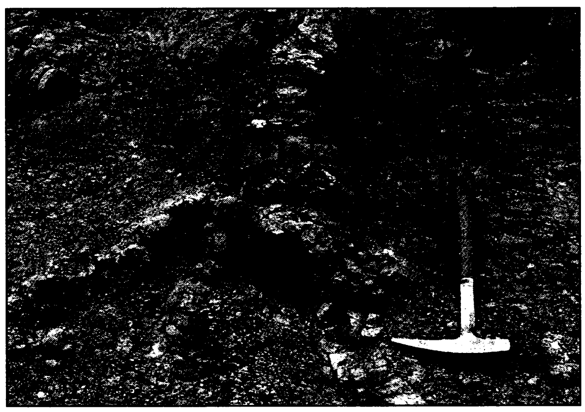
Something on Earth just won't stop fiddling with the thermostat. In the past 500 million years, the planet has shivered through ice ages lasting millions of years and sweltered through episodes of global warmth. Climatologists, eager to know what keeps jiggling the planet's temperature setting, have focused their suspicions on carbon dioxide, the same heat-trapping gas expected to drive up temperatures in coming decades. Catching this suspect in the act has been difficult, however; the atmospheres of millions of years ago are gone with the wind.

But earth scientists are now finding ingenious ways of reading the record of past carbon dioxide balances in sedimentary rock and in deep-sea sediment. The techniques are so new that their interpretation remains an uncertain art. "If you read those papers, you see a lot of 'maybes' and 'possiblys,'" says climate modeler David Rind of the Goddard Institute for Space Studies in New York City. Still, the results published in the past 2 years have generally been heartening for researchers who think the gas has been a key driver of climate change. Although there are some puzzling exceptions, the fingerprints of high carbon dioxide are all over some of the warmest periods in geological history, and its grip seems to relax during global cooling.

If the results can be firmed up, says marine geochemist Michael Arthur of Pennsylvania State University, they'll give a boost to researchers' understanding of past climates. And they may also help climatologists forecast future climate change. "We'd all like to place constraints on future global warming by using paleoclimate," says James Kasting, also of Pennsylvania State University. If climate modelers could say just how much carbon dioxide it took to, say, warm the globe by 6 to 12 degrees Celsius, as happened about 100 million years ago during the middle of the Cretaceous period, they might be able to offer better predictions.

Behind this fascination with ancient carbon dioxide, say climatologists, is the realization, some 10 years old, that atmospheric carbon dioxide can rise and fall manyfold over geological time. Getting credit for much of this consciousness raising are geochemist Robert Berner of Yale University and his colleagues. They showed how long-term changes in CO_2 can result from the shifting balance of processes that pump carbon dioxide into the air, such as volcanic activity, and processes that extract it, such as the weathering of certain rocks and the deposition of plant matter. Based on what's known about how these processes have varied over Earth's history, Berner calculated a theoretical carbon dioxide curve for the past 600 million years. The curve matches the climate record at several key points: It dips low during the great ice age of the Carboniferous and Permian periods, about 300 million years ago, for example, and rises to a high in the Cretaceous.

To researchers who had been struggling to explain the climate's ups and downs, those matchups were "really pretty impressive," says Thomas J. Crowley of Applied Research Corp. in College Station, Texas. Although some climate researchers, including Goddard's Rind, argue that changes in ocean currents may have played a bigger role in past climate changes, Berner's results encouraged Crowley and others to consider carbon dioxide a prime suspect. And now the curve has become a point of reference for many of the carbon dioxide detectives—a theory to confirm or deny. Says Thure Cerling, a geologist at the University of Utah, "Berner has nicely put up something for other people to shoot at."



STEVEN DRIESE

Written in stone. Carbonates deposited around tree roots 300 million years ago may trace ancient carbon dioxide.

Cerling himself has been taking aim at Berner's theory, and so far it has stood up well. Cerling has been reconstructing the CO_2 content of the ancient atmosphere by studying fossil soil—in particular, the veins and nodules of carbonate minerals that formed in the soil from carbon dioxide diffusing from the atmosphere or plant roots. His method relies on the fact that carbon from each source wears a badge of its origin: a specific mixture of carbon-12 and the less abundant isotope