ture 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

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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."

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


STEVEN DRIESE

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

carbon-13. Many plants, for example, take up and release "light" CO_2, containing a smaller fraction of carbon-13 than the atmosphere. By analyzing the isotopes in a carbonate sample, Cerling can estimate what fraction of the carbon must have come from the plants—and what fraction came from the atmosphere.

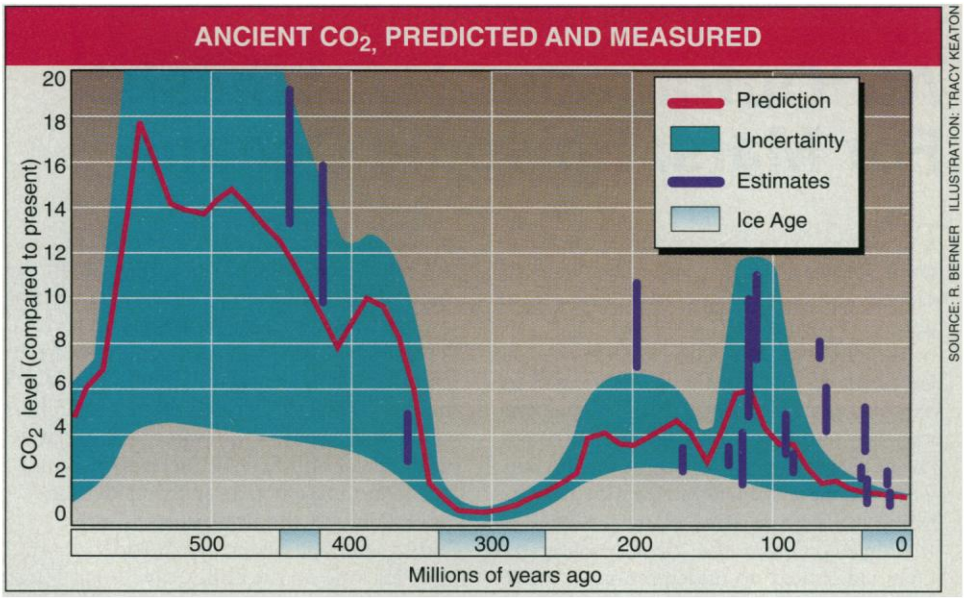
Going on to estimate the actual level of CO_2 in the atmosphere, cautions Cerling, requires assumptions about how much carbon dioxide the plants were pumping into the ancient soil. Adding to the uncertainty is the possibility that the isotopic signatures of plants and the atmosphere have shifted over geological time. "It's a dark glass we're looking through," Cerling concedes.

But Cerling says that the general drift of his results is immune to changes in assumptions. "For some of the Cretaceous soils I've been working on, no matter what your assumptions, everything ends up pointing toward high CO_2," more than six times the present level. Soils dating from the past 60 million years, a time of generally cooler climates, point to much lower CO_2—about twice the present-day level or less.

Choosy plankton. The pattern is roughly in line with what Berner predicted. And a similar trend is emerging in results from a very different quarter: the deep sea. Like land plants, the ocean's one-celled green plants, or phytoplankton, are choosy about the form of carbon dioxide they take up. But unlike land plants, which are thought to take in roughly the same isotopic mixture whatever the level in the atmosphere, the phytoplankton's intake depends on how much carbon dioxide is available. "When there's less CO_2 around, the plankton can't afford to be choosy," explains marine geochemist Kate Freeman of Penn State. As a result, the mixture of carbon isotopes in sea-floor organic matter should track the amount of carbon dioxide dissolved in the ocean when the plants were alive—a clue to gas's abundance in the atmosphere.

That realization goes back to the 1970s, says Arthur of Penn State. Various technical problems kept researchers from exploiting this record until recently, and even now it's fraught with uncertainties. But in the past couple of years, researchers including Arthur and his colleagues have tried to read it. Arthur and, independently, Freeman and John Hayes of Indiana University have come up with deep-sea histories of carbon dioxide for the past 120 million to 140 million years that show roughly the same pattern as Cerling's data. Arthur says he "definitely sees a [carbon dioxide] hump between 120 and 80 million years ago," followed by a decline. "But whether the peak was four or 10 times the present, we don't know." Freeman and Hayes also see a decline, but the initial hump was smaller—no more than four times the present level.

The reappearance of the same pattern reassures Berner: "Qualitatively, I'm happy,"



he says. The quantitative inconsistencies among the results, he says, have so far kept him from using them to tinker with his model. "But if the soil people and the marine people can agree, then I can start refining my model."

Berner and other theorists are also eager to see the techniques extended to key points in the climate record well before the Cretaceous hothouse. For example, says Berner, "what we need now are measurements for the Permo-Carboniferous glaciation [300 million years ago]," when he believes carbon dioxide fell to a low after an earlier peak.

A pair of researchers at the University of Tennessee in Knoxville is already planning a test. Geologists Claudia Mora and Steven Driese are applying Cerling's technique to soils from the Carboniferous and Permian, and they expect to have carbon dioxide estimates within the next few months. "If [they] come out with high CO_2, I'll have to do a lot of head scratching," says Berner. But Mora says the early indications are that he may get off easy. Analyzing samples even older than the Carboniferous, she and Driese saw a steep decline from levels more than 10 times higher than today in the Silurian period some 400 million years ago to three to five times higher in the Devonian, immediately before the glacial episode. Says Mora, "The models and the CO_2 results are in the same ballpark."

Still, these techniques for taking whiffs of the ancient atmosphere don't always bolster the case for carbon dioxide as the major driver of climate change. Take the oldest soil studied to date, from the late Ordovician period, 440 million years ago. Instead of soil carbonates, geologists Crayton Yapp and Harald Poths of the University of New Mexico looked at a mineral known as goethite, which snares traces of CO_2 from plants and the atmosphere in its crystal structure. By an analytical technique much like Cerling's, Yapp and Poths estimated that the Ordovician atmosphere had 16 times today's carbon dioxide—more than enough, one might think, to heat the climate to tropical levels. Yet the late Ordovician was a time of extensive glaciation.

While Yapp and Poths come up with too much carbon dioxide in an ancient ice age, marine geochemists Maureen Raymo of the Massachusetts Institute of Technology and Gregory Rau of the University of California, Santa Cruz, looking at a more recent warm period, find too little. Raymo says she and Rau decided to focus on the Pliocene epoch, about 3.5 million years ago, in part because "people say this is a greenhouse world." Half the Antarctic ice sheet had melted, and temperate conditions prevailed at latitudes that are arctic today. To stoke that kind of warmth, Crowley and other modelers had estimated, the atmosphere may have held twice as much carbon dioxide as today. Far from it, Raymo announced at last December's American Geophysical Union meeting in San Francisco: Based on the marine method, she and Rau found that Pliocene carbon dioxide was about the same as today's.

To Rind, of NASA Goddard, such results just go to show that it's too soon to declare the carbon dioxide case closed. But he agrees that, in Kasting's words, "if you really could make the CO_2 record quantitative, it could be very important." Only then might climatologists finally be able to say why the ancient atmosphere blew hot and cold—and which way it will go in the future.

–Tim Appenzeller

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