Carbon Dioxide and the Control of Ice Ages

A varying greenhouse effect may provide the leverage needed by Earth's orbital variations to control the 100,000-year ice-age cycle

The theory that climate is controlled by orbital variations had two major problems when Milutin Milankovitch advocated it in the 1940's. The limited geologic evidence that climate had changed in time with the subtle changes in the orientation of Earth's poles or the shape of Earth's orbit was not convincing. In addition, it was not clear how simply redistributing sunlight between hemispheres or seasons, as orbital variations would do, could evoke such dramatic climate changes as the waxing and waning of the recent ice ages.

The reality of orbital control of climate has now been firmly established, thanks to vastly improved geologic records and methods of analysis. And taking account of the way ice sheets grow and decay helped to amplify the effect of orbital variations in models of the climate system, but exactly how the feeble effects of orbital variations on the energy reaching Earth make themselves felt has remained largely mysterious. But new kinds of analyses of marine sediment have recently produced the strongest contender yet—atmospheric carbon dioxide—for the missing agent that boosts the climatic effects of orbital variations. This new understanding of ancient climate change has reminded researchers that future climate changes driven by fossil-fuel burning and an enhanced greenhouse effect may not be as gradual as commonly supposed.

The first solid clue that carbon dioxide and its greenhouse warming might be involved in control of the ice ages came when researchers at the University of Bern managed to extract a reliable 40,000-year record of atmospheric carbon dioxide from polar ice cores (*1*). Twenty thousand years ago, during the coldest part of the last glacial period, the concentration of carbon dioxide was 40 to 100 parts per million lower than the approximate 280 parts per million thought to have been typical before fossil-fuel burning began increasing it. About 16,000 years ago, as the great ice sheets began to melt (*Science*, 8 July 1983, p. 143), carbon dioxide began a geologically rapid increase that did not stop until it reached approximate preindustrial levels about 10,000 years ago.

Extracting the atmospheric carbon dioxide trapped in old ice without altering its apparent abundance proved a tricky feat, so researchers were relieved when Nicholas Shackleton and his colleagues at the University of Cambridge recently confirmed the ice-core record by a completely independent means (*2*). The Cambridge group uncovered in deep-sea sediments an isotopic record of how effective the ocean has been in lowering the carbon dioxide content of the atmosphere. If the ocean were lifeless—just a big puddle of water sitting beneath the atmosphere—carbon dioxide would distribute itself between water and air solely on the basis of the gas's chemical solubility. That would require the ocean to give up much of its present reservoir of dissolved carbon dioxide to the atmosphere, tripling its concentration there.

But the ocean is teeming with life near its surface. Microscopic plants and animals there take up carbon dioxide (in the form of dissolved carbonate) and build their tissues and skeletal structures out of it. When they die, their carbonate skeletons and some of their organic matter sink irretrievably into the deep sea. Once in the deep sea, much of the carbonate dissolves and the organic matter is oxidized to dissolved carbonate, which cannot mix into most surface waters because of sharp temperature and density differences between the surface and the deep waters. In effect, life in the ocean acts to pump carbon from the surface and atmosphere into the deep sea. The faster the biological pump works, the less carbon dioxide remains in the atmosphere.

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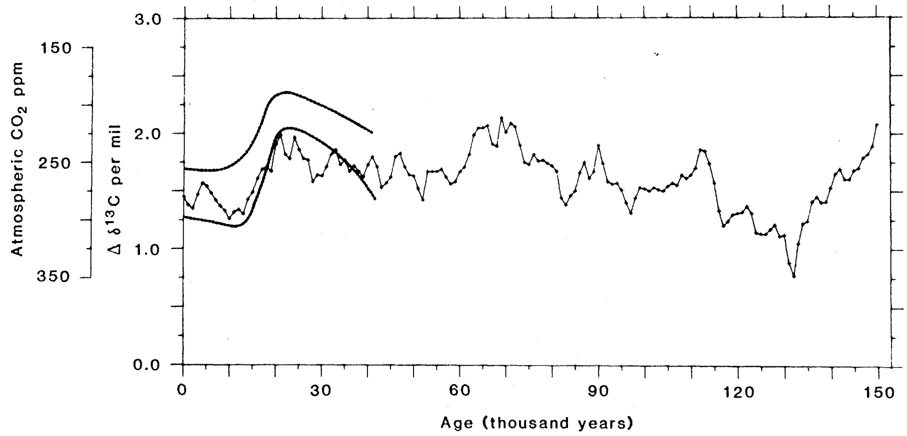
As suggested by Wallace Broecker of Lamont-Doherty Geological Observatory, the speed of the biological pump in the past and thus the amount of atmospheric carbon dioxide have been recorded in the carbon isotopes of the carbonate skeletons that escaped dissolution. Because organisms prefer the lighter carbon-12 isotope over the heavier carbon-13 isotope, the biological pump leaves heavier carbon at the surface and transports lighter carbon to deep water. The carbonate skeletons formed near the surface and those formed in deep waters by bottom-dwelling microorganisms then reflect this isotopic difference.

The Cambridge group developed a 130,000-year record of atmospheric carbon dioxide by measuring how much heavier the carbon isotopes of surface microorganisms were than the corresponding isotopes of sea-floor microorganisms at a site in the eastern tropical Pacific. This sediment record nicely matched the shorter ice-core record, showed some moderate variation during the 100,000 years of the last glacial period, and suggested the existence of even higher atmospheric carbon dioxide concentrations during the preceding warm interglacial period than during the present one.

So changes in carbon dioxide are associated with major changes in climate over thousands of years, but is one the cause of the other, and, if so, which is cause and which effect? To find out, Shackleton first extended the indirect sediment record of carbon dioxide back to 340,000 years ago. Then Nicklas Pisias of Oregon State University and Shackleton compared that record with Earth's orbital variations and changes in the volume of ice in the world, as recorded in the oxygen isotopes of the carbonates at the same eastern Pacific site. Using the statistical technique of cross spectral analysis, they found that orbital variations tend to precede changes in carbon dioxide, which in turn precede climate changes reflected in the growth or decay of glacial ice. Thus, the order of occurrence is that expected if orbital variations are the ultimate cause and carbon dioxide is an intermediate agent of climate change.

To be a convincing agent of climate change, carbon dioxide must also help to amplify the minor direct effects of orbital variations on climate. To test the adequacy of a carbon dioxide mechanism, Pisias and Shackleton added it to a mathematical model that simulates ice volume changes due to orbital variations. John Imbrie of Brown University and his son John Z. Imbrie originally constructed the model to see what effect the tendency of



Carbon dioxide and the previous ice age

The single light line is the concentration of atmospheric carbon dioxide determined from carbon isotopic differences in marine sediments. This record matches that from ice cores (range marked by heavy lines), which first showed a sharp rise (note inverted scale) in carbon dioxide at the end of the most recent ice age about 16,000 years ago. The longer isotopic record indicates even higher concentrations during the previous warm interglacial period 125,000 years ago than at present. [*Reprinted with permission from* Nature (London) *(2)*]

ice sheets to grow more slowly than they decay has on the response of climate to orbital variations. They found that the slightly nonlinear response of ice sheets did amplify the response of climate at the 100,000-year period of the variation of the eccentricity of Earth's orbit.

Ice-sheet amplification is crucial because the largest variations in the global distribution of solar energy are controlled by shorter period orbital variations, whereas the most powerful climate changes occur on the longer 100,000-year time span typical of glacial periods. The amplification of the 100,000-year signal in the ice-sheet model was sorely needed, but it fell far short of what seems to happen in nature. When Pisias and Shackleton added to the model the actual record of carbon dioxide variations, which are greatest near the 100,000-year period, the match between predicted and observed ice volume changes improved markedly. Among the improvements were an increase in the predicted volume of ice lost during warm interglacials, a gain in the amount of ice of two glacial periods, and a reduction in the variations during the last glacial period. All in all, say Pisias and Shackleton, the predicted climate variability near the periods of all three orbital variations is "essentially identical" to the observed climate variability, and the timing of glaciations and deglaciations is "much improved."

Orbital variations do seem to be able to summon carbon dioxide to do their bidding in the climate system, but exactly how they accomplish that trick is uncertain. Broecker had suggested that the speed of the biological pump would have responded to changes in ice volume. Flooding of the continental shelves as ice melting began, for example, would have led to increased removal of organic carbon and its accompanying nutrients to shelf sediments. With reduced nutrients to drive the pump, deep-sea carbon that did manage to return to the surface through upwelling of water would accumulate there and in the atmosphere as carbon dioxide.

Broecker no longer argues that glacial transitions are accelerated solely by changes in the nutrients stored on the continental shelves. For one thing, this mechanism requires that ice volume changes precede carbon dioxide changes, contrary to the new results of Pisias and Shackleton. In addition, Hans Oeschger and Bernard Stauffer of the University of Bern have recently reported (*Science*, 9 December 1983, p. 1107) that, on the basis of ice-core studies, atmospheric carbon dioxide varied by as much as 50 to 80 parts per million within as little as 100 years. The overall change at the end of the last glacial period was less dramatic, but some sharp jumps were also too rapid to depend on the relatively slow exchange of nutrients between sediments and the ocean (*3*).

In their search for some means of rapidly changing atmospheric carbon dioxide, researchers are looking for ways either to change how the pump-driving nutrients already in the ocean are used or to alter what exchange does occur between the deep sea and the surface. Several ways of doing this were presented at a recent meeting on the carbon cycle,* but they all depend on the special connection between the atmosphere and the deep sea provided by high-latitude surface waters. It is here that the deep sea, three-quarters of the ocean's volume, pierces the density gradient barrier and makes direct contact with the atmosphere through less than 4 percent of the ocean's surface area. Deep and surface waters mix, providing more nutrients than microscopic plants, called phytoplankton, can use.

Although modelers agree that the high-latitude oceans are probably the key, they do not yet agree exactly on how that part of the ocean controls atmospheric carbon dioxide. One way to change the speed of the biological pump at these high latitudes would be to have the phytoplankton use more of the available nutrients. Under present conditions, too little light reaches high latitudes for full nutrient utilization, but orbital variations can change the amount of light falling there. Changes in ocean circulation at high latitudes or between high and low latitudes could do the same. The flow of carbon dioxide to the atmosphere from upwelled deep water could also be reduced if high-latitude circulation became less vigorous.

Such mechanisms have some major hurdles ahead of them. For one, they predict that the increased oxidation of organic matter pumped into the deep sea during glacial periods will reduce oxygen concentrations to zero in a thick layer of the ocean. No evidence of this has yet been found, although the search has been far from exhaustive. These models also predict heavier carbon isotopes in high-latitude surface waters during glacial periods, but Shackleton has noted that what data are available from Antarctica actually show the reverse. And finally, although these internal ocean mechanisms are faster than those requiring exchange with sediments, the ocean still requires about 1000 years for one complete circulation from top to bottom. The rapid carbon dioxide oscillations during the last glacial period took only 100 years. Until researchers have a better idea of what drove carbon dioxide and climate through such rapid variations in the past, they will remain uneasy about today's increasing atmospheric carbon dioxide and its expected greenhouse effect.—**RICHARD A. KERR**

References

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3. B. Stauffer, A. Neftel, H. Oeschger, J. Schwander, *Ann. Glaciol.*, in press.

*Chapman Conference on Natural Variations in Carbon Dioxide and the Carbon Cycle, Tarpon Springs, Florida, 9 to 13 January 1984; E. T. Sundquist and W. S. Broecker, coconveners. Those modeling the role of the high-latitude ocean include W. Broecker and T. Takahashi, Lamont-Doherty Geological Observatory; F. Knox and M. McElroy, Harvard University; J. Sarmiento and J. R. Toggweiler, Princeton University; and U. Siegenthaler and Th. Wenk, University of Bern.