CLIMATE

Ice, Mud Point to CO_2 Role In Glacial Cycle

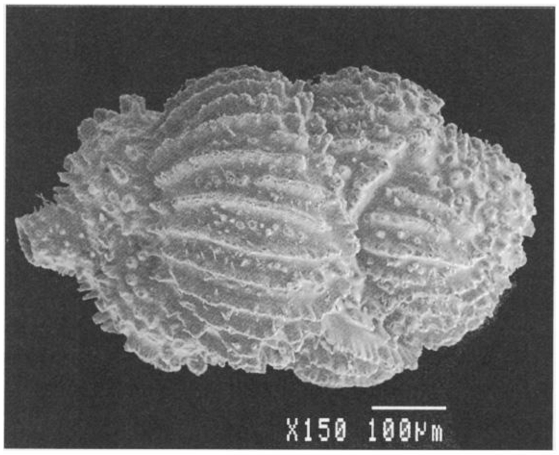
Antarctic ice and deep-sea records suggest that orbital variations work through carbon dioxide, not ice sheets, to drive the ice ages

Every 100,000 years or so for the past million years, kilometers-high sheets of ice have ground southward from the Arctic. The vast glaciers scour landscapes and drive all life before them. Yet if the effects of the ice ages are far from subtle, their exact causes have left researchers scratching their heads for more than a century. Somehow, the rhythmic stretching of Earth's orbit seems to drive glacial cycles, but how this feeble "orbital variation" could cascade through the climate system of air, land, water, and ice to produce such monstrous climate shifts has remained a mystery. On page 1897 of this issue of *Science*, paleoceanographer Nicholas Shackleton of the University of Cambridge finds a likely strongman to transmit and enforce the orbital variations' demands: carbon dioxide. Comparing records preserved in deep-sea muds with those in antarctic ice, he finds that orbital variations may muster carbon dioxide into and out of the atmosphere, and the resulting waxing and waning of greenhouse warming may drive the glacial cycle.

"It's quite an exciting development," says paleoceanographer John Imbrie, professor emeritus at Brown University. "He's made a major step forward." Imbrie, Shackleton, and James Hays of Lamont-Doherty Earth Observatory in Palisades, New York, co-authored the 1977 paper in *Science* that made orbital variations the leading candidate for the ultimate driver of the ice ages. Imbrie went on to suggest that the ice sheets themselves amplify the weak orbital signal, but Shackleton concludes that ice is farther down the chain of command; carbon dioxide is the executive officer who hands Earth its climatic marching orders.

Shackleton reached his conclusion by precisely comparing geologic records in two different media, a method that enabled him to tease out intimately entangled climatic influences with unprecedented accuracy. First he consulted the paleoceanographers' mainstay, bottom muds containing fossil skeletons of microscopic marine animals called foraminifera. The mix of heavy and light isotopes of oxygen in the forams' carbonate skeletons depends partly on the mix of isotopes in the seawater the forams lived in and partly on the water's temperature. The composition of the seawater, in turn, depends on how much ice is trapped on land at any time—a factor long considered the dominant influence on such isotopic records. The oscillating oxygen isotopes of forams seemed to show that ice volume varied in step with the 100,000-year variation in the shape or eccentricity of Earth's orbit, although the correlation was not impressive.

To get a cleaner identification of changing ice volume, Shackleton turned to bubbles in the 400,000-year-long ice core retrieved from the antarctic ice sheet by Soviet drillers at Vostok station and analyzed by a team of French glaciologists headed by J. R. Petit of the Laboratory of Glaciology and Geophysics in St. Martin d'Heres. Because bubbles in glacial ice come from the atmosphere, their oxygen-isotope composition—unlike that of foram shells—does not respond to ocean temperatures. But the composition is sensitive to the volume of ice in the world, because isotopic changes in seawater oxygen are passed on to atmospheric oxygen through marine photosynthesis. Thanks to that difference in response, Shackleton could separate ocean-temperature changes from ice-volume changes.



Two tales to tell. Bottom-dwelling foraminifera record both temperature and the volume of glacial ice.

To Shackleton's surprise, deep-sea temperature accounted for more variation of oxygen isotopes than ice volume did. And orbital eccentricity, deep-sea temperature, and atmospheric carbon dioxide as recorded in Vostok gas bubbles all varied in step, on the same 100,000-year cycle. Ice volume, however, lagged behind.

Shackleton sees the lockstep of eccentricity, greenhouse gas, and temperature as a sign of cause and effect. In his view, at the beginning of glaciation changes in eccentricity—presumably by shifting the distribution of sunlight across the globe—could have decreased atmospheric carbon dioxide, weakening the greenhouse and cooling the ocean and atmosphere. At the end of an ice age, the changes are in the opposite sense. Those changes are relatively rapid and would appear to coincide; the sluggish ice volume would lag behind. That delay rules out ice as a prime mover, Shackleton says; it's only a follower.

Shackleton's results impress many researchers who specialize in sorting out the cause of the ice ages. The paper "is really well argued," says geophysicist Richard Peltier of the University of Toronto. "It has inevitable drawbacks because of the short record," but it would appear that "carbon dioxide is a primary driver, not just a weak feedback."

Peltier says his own computer models reinforce that conclusion. Hoping to show that ice sheets themselves were crucial to glacial cycles, he developed a model that included not only orbital forcing and carbon dioxide variations but also the way ice sheets grow and decay. The ice turned out to be essential for the distinctively abrupt end of an ice age, but not crucial the way carbon dioxide seems to be. "The model only works because it includes the forcing from carbon dioxide," Peltier says. "If we exclude that, we get no glacial cycle. The ice dynamics just doesn't do it for you at all without carbon dioxide."

Even if Shackleton's elimination of ice as a primary factor and support for carbon dioxide stand up, "there's a lot of questions that remain," says geochemist Daniel Schrag of Harvard University. In particular, he says, no one knows how orbital variations would send the carbon dioxide into and out of the atmosphere.

And there are likely to be other significant factors besides carbon dioxide, notes climate modeler André Berger of the Catholic University of Louvain in Belgium. "I have quit looking for one cause of the glacial-interglacial cycle," he says. "When you look into the climate system response, you see a lot of back-and-forth interactions; you can get lost." Schrag agrees. "It's a complicated problem," he says. "We still don't know the cause of the ice ages."

–RICHARD A. KERR

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