Milankovitch Climate Cycles: Old and Unsteady

Orbital variations have affected climate for at least 8 million years, but their impact has been mediated by other influences

Widely touted as *the* "secret of the ice ages," variations in the orbital motions of Earth do indeed appear to be crucial to the waxing and waning of the great ice ages over the last 3 million years. But researchers are finding that the theory of orbital variations, as proposed in 1941 by the Serbian Milutin Milankovitch, cannot be the only secret. Looking back into the geological record before the ice ages, paleoceanographers are discovering that orbital variations affected the ocean and climate then too, at least as early as 8 million years ago and perhaps 30 to 40 million years ago. But these researchers are startled by the unpredictability of the effects. Some still mysterious influence or influences, secrets not only of the ice ages but of climate change in general, must modulate the effects of each of the cyclic orbital variations.

Researchers have only recently established the geological antiquity of the effects of orbital variations. Ted Moore of the University of Rhode Island, Nicklas Pisias, then at Rhode Island but now at Oregon State University, and Dean Dunn of Rhode Island found a record of orbital variations preserved in the sediments at the Deep-Sea Drilling Program's (DSDP) site 158 in the equatorial Pacific.* Orbital variations include slow, cyclic changes in the orientation of Earth's axis of rotation and in the shape of Earth's orbit around the sun. The orbital cycles appeared as variations in the proportion of calcium carbonate, the skeletal mineral of some marine microscopic animals, in sediments deposited between 5 and 8.5 million years ago. Moore and his group also studied the carbonate cycles in sediment cores deposited over the past 2 million years (the Pleistocene epoch). Although relatively easy to measure, carbonate is not a simple indicator of climate. Climate-related changes in the dissolving power of seawater, in sea level, in ocean circulation, and in the rate of erosion of the continents can all affect the proportion of carbonate in sediments.

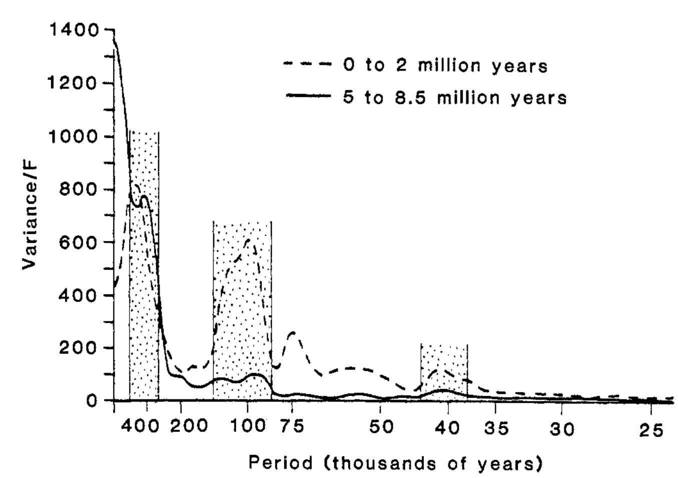
By using a statistical technique called spectral analysis, Moore and his colleagues identified three different cycles of changing carbonate content in the two cores. One cycle had a period of about 400,000 years and appeared in both cores. Madeleine Briskin and James Harrell of the University of Cincinnati had found a similar periodicity in both Atlantic and Pacific sediments of the Pleistocene. They had assumed that a particular orbital variation with a period of 413,000 years, the cyclic change in the ellipticity or eccentricity of Earth's orbit, had induced changes in climate that were reflected in changes in the sediment.

Using cross-spectral analysis, Moore's group demonstrated a correlation between the eccentricity cycle and the carbonate content of their cores. Spectral analysis provides an objective measure of the duration of a cycle, and this comparison between the sedimentary cycle and the calculated eccentricity cycle showed that the two were in phase over the last 8 million years. Both tasks necessitated the use of some sort of statistical test because the 400,000-year cycle, which itself is not precisely regular, was jumbled together with other Milankovitch cycles and with random variability, which accounted for about 50 percent of the total variability.

Two other orbital cycles, which had already been identified in sediments of the past half million years, also showed up in the 2-million-year-long Pleistocene carbonate record. One cycle had a period of 100,000 years and was in phase with a 100,000-year cycle in eccentricity. A minor cycle of 41,000 years matched the variations in the tilt of Earth's axis.

Although the 100,000-year cycle dominated climatic variability during the Pleistocene ice ages, accounting for more than half of the variability due to the three orbital cycles and 29 percent of the total variability, it had a minor effect 5 to 8.5 million years ago. Even after the 400,000-year cycle was used to adjust or "tune" the dating of the core, the 100,000-year cycle accounted for six times less variability than it did during the Pleistocene. The variability of the 400,000-year cycle remained unchanged, which meant that the variability of the carbonate record, and presumably of the climate, was twice as great during the past 2 million years as it was 7 million years ago. Warren Prell of Brown University and James Gardner of the U.S. Geological Survey (USGS) in Menlo Park, California, also failed to find much evidence of a 100,000-year cycle in pre-Pleistocene sediments at DSDP site 502 in the western Caribbean and at site 503 in the eastern equatorial Pacific. They did apparently find evidence of the 41,000-year cycle (measured as 43,000 years) in their 7-million-year sediment record, as well as evidence of a 250,000-year cycle.

Because the orbital variations presum-



These variance spectra show how much stronger the effects of the 100,000-year cycle were over the past 2 million years (dashed line) than 5 to 8 million years ago (solid line). The larger the peak, the more variability in the carbonate content of the sediment (and presumably in climate) is attributable to cycles having that period. The variability attributable to the 400,000-year cycle remained the same, but that in the 100,000-year cycle was about six times greater during the more recent period. Variability having periods between 40,000 and 100,000 years also increased dramatically. [Moore, Pisias, and Dunn, in Marine Geology]

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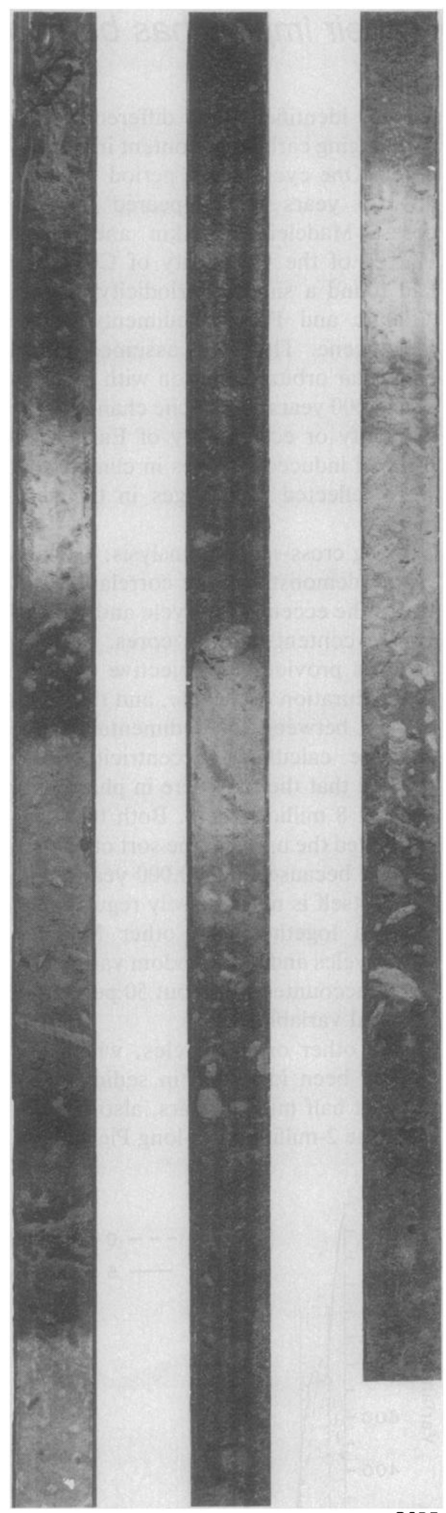
ably were repeating themselves faithfully over the past 8 million years, an additional influence must have magnified the climatic effect of the 100,000-year cycle during the past 2 million years. For that matter, researchers have always found Milankovitch's calculated climatic effects of the eccentricity cycle to be far too small to explain the observed Pleistocene climate cycles (*Science*, 14 July 1978, p. 144). A popular mechanism for amplifying the effects of orbital variations is the behavior of glacial ice sheets themselves—they grow much more slowly than they decay. This asymmetric nature of ice sheet life cycles has helped to make computer models of the 100,000-year climate cycle more realistic, although not yet entirely accurate. The Rhode Island group proposes that the existence of Northern Hemisphere ice sheets, which formed since 3 million years ago, may thus be essential to the appearance of a strong 100,000-year cycle. The strong 400,000-year eccentricity cycle might in turn result from the presence of the Antarctic ice sheet, which formed about 13 million years ago.

John Imbrie of Brown, who has been working on models to explain the exceptional strength of the 100,000-year cycle, agrees that amplification by ice is "a plausible hypothesis to follow." That northern and southern ice should modulate the effects of different orbital cycles seems a reasonable possibility, he says, because the northern and southern ice masses are so different. Antarctica's ice lies mainly on land near the pole surrounded by an equally large area of sea ice that melts each year. In the Northern Hemisphere, the major ice sheets tend to form farther from the pole, south of 70°N, and have a polar sea to the north and subpolar seas to the south.

Although the major ice sheets may play their own roles in modulating the cycles having longer periods, cycles with periods shorter than 100,000 years seem to have been modulated at times when major ice masses were probably absent. Walter Dean of the USGS in Denver, Pavel Čepek of the Institute for Geological Research and Natural Resources in Hanover, West Germany, and Gardner studied sedimentation during the past 60 million years in a core recovered at DSDP site 366 on the Sierra Leone Rise off West Africa. For most of the core length there are cyclic variations in the carbonate content, which were probably induced by changes in the flow of the bottom current there, the researchers say. But no single cycle appeared in all of the periods studied. Between 5 and 38 million years ago, cycles having an average period of 44,000 years dominated among the shorter cycles. (Dean and his colleagues measured individual cycles in a given period of time and averaged their durations rather than use spectral analysis.) The 44,000-year carbonate cycle was presumably induced by the variation in tilt.



DSDP

Sedimentary cycles

These sediments of the past million years were recovered at DSDP site 503B in the eastern equatorial Pacific using the hydraulic piston corer. The alternating light and dark layers of varying carbonate content reflect cycles of 20,000 to 40,000 years.

In earlier time, the tilt cycle was absent. In its place, they found a dominant cycle around 43 million years ago with an average period of 19,000 years. That is close to the 21,000-year cycle found in Pleistocene sediments that has been linked to Earth's precession cycle. Precession is the wobble of Earth's axis. Around 50 million years ago, the dominant cycle had an average period of only 7000 years.

Because of studies such as these, researchers are beginning to see that different periods of geological time experience different amounts of climatic variation with varying frequencies. Traditionally, geological time is divided into segments on the basis of the climate-related appearance and extinction of particular species of plants and animals. Some researchers are now dividing time in terms of climate variability and finding entirely different boundaries.

Prell found that the Pleistocene is divided about in its middle by a shift from one "mode" of variability to another. Before about 1 million years ago, the oxygen isotopic composition of carbonate, a measure of the amount of glacial ice in the world, indicated less ice and smaller variations between the peaks and troughs of ice accumulation cycles. Since 1 million years ago, there has been more ice and greater variability. A similar shift between modes occurred about 3 to 3.5 million years ago in the middle of the Pliocene epoch, Prell says. Shifts between modes may mark changes in the climate system, such as the closing of the Isthmus of Panama, that alter the response of the system to the orbital variations, he says.

Another way of using cycles to divide time may greatly improve the precision of the geologic time scale. The events of known age now used to assign dates to particular points in a sediment core, in addition to extinctions, include changes in the magnetic field of Earth and the deposition of layers of volcanic ash. All of these are often widely and irregularly spaced through time. If one of these markers is not near the point to be dated, the assigned age might have a precision of a million years or more. But the orbital variations tick off markers every 0.4, 0.1, and 0.04 million years, and the effects of these on the sediments have been, in some cases, recorded for tens of millions of years. Thus, the effects of orbital variations might provide a clock with which to date older sediments with a precision that is ten times greater than now possible.—RICHARD A. KERR