nificant deterioration of air quality in clean air regions. In the case of the first two regulations mentioned, the executive committee concluded that EPA's own analysis of the economic impact was satisfactory.

In the case of the proposed "significant deterioration" regulation, which has now become final, the public comment period had closed before the committee took it up and, for this reason, it was never formally placed on the RARG agenda. Nevertheless, numerous discussions took place among people at EPA, CEA, and CWPS, with the result that EPA finally decided to change the scope of its original proposal in a way that reduced its coverage of affected companies by half, yet "without any significant increase in emissions expected."

The next big EPA regulatory proposal likely to be taken up by RARG will be the one (not yet issued) for new source performance standards (NSPS) for large fossil fuel boilers. Already, economists at CWPS are using preliminary air quality modeling data from EPA and the Department of Energy in an attempt to see what standards will make the most sense economically as well as environmentally.

Environmentalists such as Robert Rauch, an attorney with the Environmental Defense Fund, believe that the new economic and inflation review process leads to legal or procedural improprieties when pressures are applied to regulatory agencies such as CEA or CPWS either before a regulation has been formally proposed or after the public comment period has closed. Rauch is convinced that issuance of the proposed NSPS regulations would not have slipped several months behind schedule had EPA not felt under strong pressure to moderate the standards with a view to accommodating greater coal consumption.

Yet, in principle, the testing of proposed environmental regulations against standards of economic efficiency is hard to fault. Or at least it is so long as those doing the testing are committed to the Carter Administration's stated determination not to sacrifice environmental quality to economic expediency.

—LUTHER J. CARTER

RESEARCH NEWS

Climate Control: How Large a Role for Orbital Variations?

Variations in the earth's climate occur from year to year, over periods of hundreds of millions of years, and on every time scale in between. Climatologists have known that some of this variability is not random, but that it occurs in more or less regular cycles, such as the comings and goings of the ice ages. But researchers have generally been at a loss to explain how these cycles are controlled.

A 150-year-old theory of climate control, now known as the Milankovitch theory, has recently gained widespread acceptance as a factor in the long-term variation of climate over the last several hundred thousand years. The theory holds that regular, easily predicted changes in the orientation of the earth's axis of rotation and the shape of its orbit affect the distribution of sunlight over the earth. This varying distribution would then control the timing of glacial epochs. Only within the last few years has convincing evidence been extracted from the geological record to support the contention that the predicted climate variations actually occurred.

Even though a link between orbital variations and climate has finally been generally accepted, there is still doubt among many researchers as to whether the Milankovitch theory can fully explain the observed variations or only a small portion of them. Part of the problem is that studies of deep-sea sediment cores have revealed not only the 23,000-year and 41,000-year climatic cycles predicted by the theory, but also an unexpected 100,000-year cycle that dominates the two shorter cycles. In addition, it is not yet known how much of long-term climate variability can be accounted for by these three cycles.

The first suggestion that orbital variations might affect climate was apparently made in 1830 by the astronomer John Herschel. The idea was not forgotten, having been refined several times since. It was most recently revived by Milutin Milankovitch, a Serbian, who published detailed calculations in 1941. But there have always been a large number of competing theories. These include theories that invoke factors external to the climate system, such as changes in the light output of the sun, the concentration of interstellar dust, the earth's magnetic field, or the amount of volcanic dust injected into the atmosphere. Researchers have also considered the possibility that an active component of the climate system, such as the continental ice sheets themselves, might respond to the rest of the system by cycling with its own characteristic periodicity. Of all these proposals, only the Milankovitch theory has been supported so far by substantial physical evidence. This may be because it is the only theory that can be used to predict precisely the duration of periodic changes in climate.

Exact predictions of periodicities are possible because they depend on characteristics of the earth's axis of rotation and orbit that are readily calculable far into the past. The tilt of the earth's axis away from the plane of the earth's orbit, the obliquity, is now 23.5°, but it slowly varies between 22.1° and 24.5°, completing one cycle every 41,000 years. Since it is obliquity that causes the seasons, a cyclic variation in the obliquity produces a cycle in the strength of the contrast between seasons.

While this gentle nodding of the axis occurs, the axis also precesses, or changes its direction. At the moment, the axis points in the direction of Polaris, the North Star. As the axis precesses, it describes a circle among the stars. Precession also affects the contrast of the seasons because it determines at what point on the earth's elliptical orbit winter and summer occur. Winters occurring near the earth's closest approach to the sun would be warmer on the average than those occurring at its farthest point. Spring and fall seasons would be proportionately cooler. The precession cycle has a period of about 21,000 years.

The ellipticity, or eccentricity, of the earth's orbit is not constant, either; it varies in a 105,000-year cycle. According to the Milankovitch theory, this cycle should only modulate the size of the precession effect, and should cause no significant climate cycle of its own.

Neither the 41,000-year obliquity cycle nor the 21,000-year precession cycle involve a change in the total amount of sunlight falling on the earth, as a change in the output of the sun would. Rather, they affect how much sunlight a particular latitude receives at a particular season. At one point in a cycle, for example, 5 percent more sunlight than average might fall at 60°N during the summer, but 5 percent less would fall at the same latitude in the winter. Despite Milankovitch's detailed calculations of these changes in seasonal contrasts, there was still no agreement about what the resulting climates should have been like and the available geological climate records were not at all convincing.

The theory received increased attention in the 1960's when suggestive favorable evidence began to accumulate. Several studies of coral terraces in Barbados, Hawaii, and New Guinea indicated that the seas rose to high levels (and ice caps shrank to small sizes) at about 80,000, 105,000, and 125,000 years ago, dates that are consistent with the theory. Additional information was provided by the records of oxygen isotope variations, which respond mainly to changes in the size of the ice sheets; this information was obtained from deep-sea cores by Cesare Emiliani of the University of Miami. But uncertainties in the dating of older samples and the complexities of interpreting the climate record frustrated attempts to definitely link orbital variations and climate.

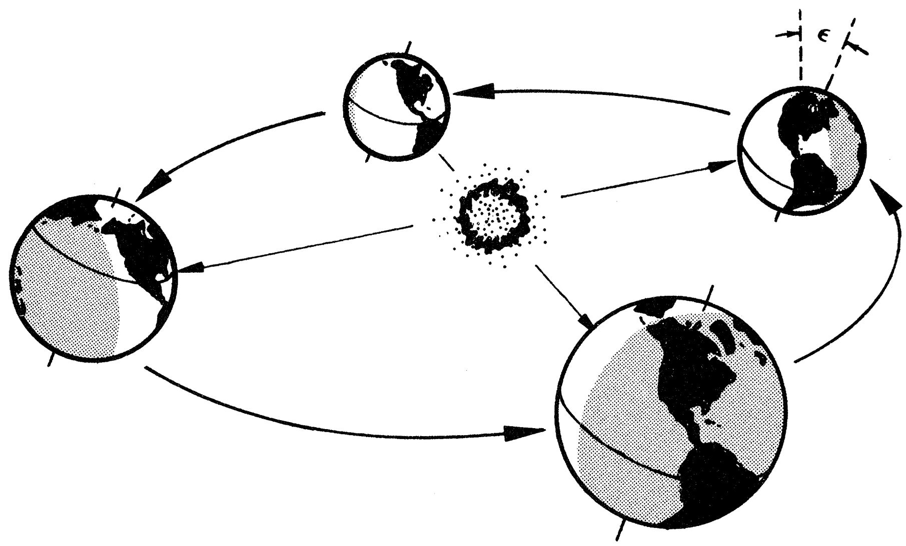

Fig. 1. The Milankovitch theory links climatic cycles to variations in the orbital characteristics of the earth by way of contrasts between seasons. The orbital characteristics include the tilt of the earth's axis (ϵ), the direction of the axis (to the right in this diagram), and, in a minor way, the ellipticity of the earth's orbit (exaggerated here for illustration). Northern Hemisphere summer is shown at left.

Using a combination of several dating techniques and the mathematical method of spectral analysis, researchers within the CLIMAP project (Climate: Long-range Investigation, Mapping, and Prediction) have been able to show that at least some cyclic patterns of climate are linked to orbital variations. In a recent study, Nicklas Pisias of the University of Rhode Island measured within a deep-sea core the rates at which calcium carbonate and silica, skeletal components of free-floating microscopic plants and animals, accumulated at a site in the Panama Basin. The silica rate reflects the size of a particular type of near-surface biological community, which waxed or waned in response to changes in the climate. The carbonate rate reflects the climate-related ability of bottom waters to dissolve accumulated carbonate. By using spectral analysis to extract the strongest cycles from the total climate record, Pisias found that the accumulation of carbonate showed a 23,000-year periodicity, close to the precession cycle, and that silica accumulation suggested a 100,000-year cycle, close to the eccentricity cycle. Both of these cycles also appeared in the oxygen isotope record of a core from another site.

The most convincing study to date is that of James Hays of Columbia University, John Imbrie of Brown University, and N. J. Shackleton of Cambridge University, all participants in CLIMAP. They measured climatic indicators in a deep-sea core record spanning 450,000 years and found climate variations with periods of 23,000, 42,000, and 100,000 years. As further proof, they demonstrated that these cycles were generally in step with their appropriate orbital cycles for the last 350,000 years.

Hays and his co-workers selected a sediment core record that they felt was best suited to test the Milankovitch theory. Because no one core seemed ideal, they actually analyzed parts of two cores from nearby sites midway between Africa, Australia, and Antarctica, and spliced the climate record from the upper part of one to the lower part of the other. This gave them, in effect, one long, continuous core that had accumulated fast enough to record cycles considerably shorter than 20,000 years. Also, the core locations, directly beneath the present-day boundary separating cold Antarctic surface waters from warmer water to the north, made the sediment record particularly sensitive to changes in climate. During the extreme climate fluctuations of the ice ages, this boundary would have moved back and forth over the core sites. Major changes in climate would thus have been recorded as relatively sharp changes in the chemical and biological properties of the microfossils that had sunk to the bottom and formed the sediment.

Analyses of the cores included measurements of three different climatic indicators. Oxygen isotope analyses showed how the size of the ice sheets varied in the Northern Hemisphere, where most of the ice is stored during colder periods, and allowed correlation with other core records. Abundances of selected temperature-sensitive species of radiolarians, microscopic animals that live near the surface, indicated changes in water temperature above the core sites. The abundance of a single radiolarian species was used as an indicator of the presence of a specific set of water properties. Two of the three indicators, the volume of the ice sheets and the temperature of the surface water, consistently showed cycles with the three orbital periods, while changes in the indicator of water properties provided a less reliable record of the two shorter orbital cycles. The dominant cycle always had a period of 100,000 years, which is not, strictly speaking, a Milankovitch cycle.

Additional supporting evidence has been developed since Hays, Imbrie, and Shackleton reported their results. Ross Heath, Pisias, and Ted Moore, all of the University of Rhode Island and members of the CLIMAP project, studied sediment cores from three widely separated sites in the Pacific. Although they placed less emphasis on the absolute dating of climate changes, they did find that changes in different measures of climate in the same core remained in step with each other and that these changes had periods similar to those predicted by the Milankovitch theory. Also, Imbrie believes published data on climate-induced variations in a terrestrial pollen record reveal a 40,000-year periodicity.

Although evidence is accumulating in support of the Milankovitch theory, significant problems remain to be resolved.

For example, the dating of climatic events continues to be a problem. Some CLIMAP studies are being held in abeyance until general agreement can be reached concerning the best geochemical means of dating the samples involved. Hays' group deduced dates for various depths in their cores from both geochemical and nongeochemical data, but then, assuming that Milankovitch cycles were present, they stretched and compressed the time scale until the strongest cyclic signals appeared in the climatic variables. While this is a reasonable approach to the problem, Moore notes, more precise dating control by various geochemical methods is desirable. Improvement in dating is particularly needed in the case of older sediments. For example, Hays' group was unable to tell whether the mechanism of climate change was different before 350,000 years ago, or whether their dating was simply not accurate enough.

While most researchers now believe that the influence of orbital variations on climate is real enough, many still hold strong reservations about the ability of orbital variations to actually control major climate cycles. One problem is the unexplained dominance of the 100,000-year cycle. This cycle has been seen in many geological records, but its only connection with orbital variations is through the supposedly insignificant effect of variations in the eccentricity of the earth's orbit. The eccentricity cycle causes at most a 0.1 percent change in the total sunlight, or insolation, falling on the earth. The problem is to demonstrate a physical mechanism that can link the small eccentricity effect on insolation to the large changes in climate represented by the 100,000-year cycle. In any case, even the magnitudes of the shorter cycles need to be explained by some amplifying effect within the climate system.

Several groups have approached this problem by calculating the changes in a simple, mathematical model of climate that is subjected to the predicted changes in insolation, and they have obtained "tantalizing but not convincing" results. Most of these calculations depend on an interaction between variations in insolation and the albedo, or reflectivity, of the earth to produce climate changes of significant size. But most models developed so far are still slightly out of phase with reality (calling for a cooler climate at present), do not generate more than half of the observed range of climate variation, and do not show a 100,000-year cycle.

Isaac Held of the Geophysical Fluid Dynamics Laboratory at Princeton University and Max Suarez of the University of California at Los Angeles developed a model that approximately reproduces the timing and size of the 23,000- and 41,000-year cycles predicted by the Milankovitch theory. It also demonstrates the important role of albedo-insolation interaction, or positive feedback, as it is called. Their model generates the largest climatic changes when the largest insolation changes occur during the Northern Hemisphere summer. Positive feedback occurs, for example, when a small increase in insolation is able to cause a large decrease in the land area covered by snow. This results in a large decrease in albedo. The additional sunlight that is absorbed rather than reflected back into space warms the climate and contributes to further decreases in snow cover. Northern Hemisphere summer seems to be the best time for this to happen because of the large land area involved and the small latitudinal temperature gradient of summer.

David Pollard of the California Institute of Technology has added an ice sheet component to a simplified version of Held and Suarez's model. The ice sheet component of the model, the general features of which were developed by Johannes Weertman of Northwestern University, allows for the growth and decay of the ice sheets in accordance with some simplified principles of glaciology. This more complex but still incomplete model fails to produce the 100,000-year cycle. Pollard thinks that this cycle would appear only if some component of the climate system responds much more sharply to, say, an increase in insolation than it does to a decrease. His glacial component has such a nonlinear response, but it apparently is not great enough. Imbrie has inserted a nonlinear response to the eccentricity cycle of insolation in a simple statistical model, which does generate a 100,000-year climate cycle. Edward Birchfield of Northwestern and Weertman have also seen a suggestion of an eccentricity-related cycle in their own calculations with a nonlinear model. But none of these results has provided convincing evidence to climatologists looking for the physical mechanisms linking orbital variations to climate.

Significance Questioned

Another fundamental question, currently being considered by CLIMAP researchers, is whether the three observed cycles account for most of the climate variability having periods in the range predicted by Milankovitch, or only for a small part of it. Hays, Imbrie, and Shackleton originally suggested that about 80 percent of the total variability observed in their sediment record was associated with the three most obvious cycles. They concluded "that changes in the earth's orbital geometry are the fundamental cause of the succession" of recent ice ages.

This conclusion has been questioned by several researchers. Carl Wunsch of the Massachusetts Institute of Technology concedes that the question presents difficult statistical problems, but he believes that the amount of variability explained by the three cycles is closer to 10 percent than 80 percent. David Evans of the University of Rhode Island and Howard Freeland, now at the Institute of Ocean Sciences, Victoria, British Columbia, agree that a significant background of variability probably exists on which the Milankovitch cycles would be superimposed. They point out that the broad spectrum of background climatic variability commonly observed in geological records, especially the shorter period variability, could be generated by other processes, such as those in the stochastic, or random, theory of climatic variation proposed by Klaus Hasselmann of the Max Planck Institute. This possibility is now being investigated by CLIMAP workers and Claude Frankignoul at MIT.

Wallace Broecker of the Lamont-Doherty Geological Observatory also believes that the evidence supports climate modification by orbital variations, but denies that control of the ice ages has been demonstrated. He suggests that, while spectral analysis of long geological records indicates a straightforward correlation, comparison of reliably dated individual climatic events with insolation variations reveals major inconsistencies. While Hays now thinks that the 80 percent figure does need to be reevaluated, he believes that the control of ice age timing by orbital variations is still supportable.

Climate cycles of even shorter periods than Milankovitch predicted are being identified, some much too short to be related to orbital variations. As Stephen Schneider of the National Center for Atmospheric Research and others have suggested, long-term climate variations may well be subject to control by a combination of Milankovitch cycles and other external controls, as well as by regulating agents within the climate system. Clear-cut confirmation of any cycles will probably require better dating, better statistics, and a better understanding of underlying mechanisms.

—RICHARD A. KERR