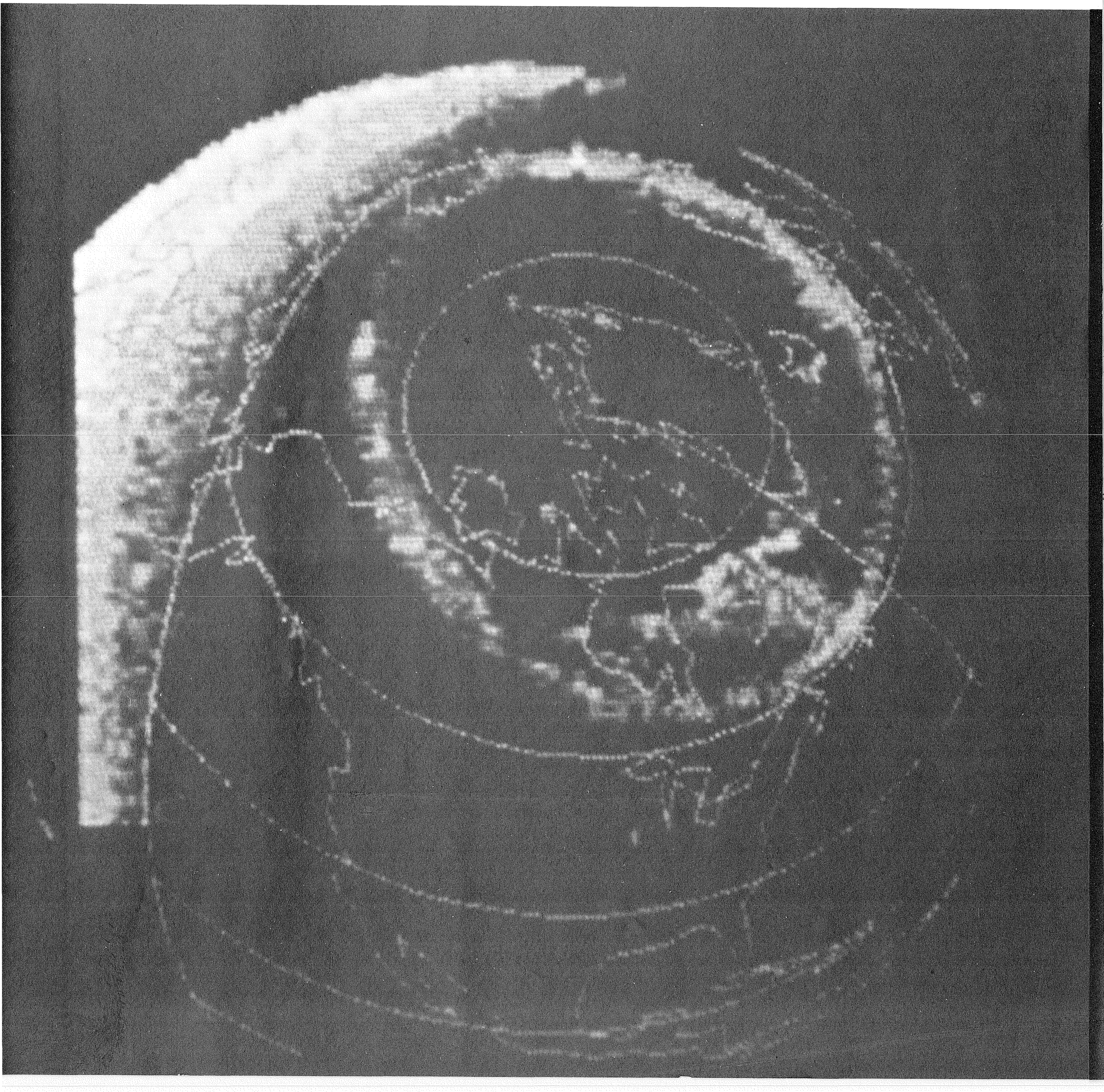
SUN-EARTH

Energizing the Climate Cycles

by Marcia Bartusiak



As scientists develop confidence in their understanding of the sun-earth relationship and how it affects climate and weather patterns, they find human effects on the system threatening to overwhelm the natural ones.

Both in documented reports and in anecdotal histories, the sun's behavior has long been coupled to phenomena on earth. The connection itself was forged more than 4.5 billion years ago, when the sun and earth both emerged from the same condensing cloud of celestial dust and gas. In the process, the earth came to orbit the sun within a narrow zone that is fed by the sun's electromagnetic and particle radiation at intensities that will support life.

Located 150 million kilometers from the earth, the sun is the ultimate engine for an array of terrestrial processes. Solar radiation reaches the earth in a continuous flow that amounts to 1,367 watts of energy per square meter, fueling the planet's biosphere and driving its weather and climate machines. Approximately 30 percent of this energy is immediately reflected back into space, primarily by clouds; 16 percent more is attenuated by water vapor, dust, ozone, and the like; the rest is absorbed and then reemitted. The tropical regions receive the greatest amount of energy, and the higher latitudes less; the resulting imbalance sets global air-circulation patterns in motion.

The true complexity of the sun-earth connection was not fully appreciated until the arrival of the space age. Using satellites, researchers were able to establish the presence of particle-radiation belts around the earth, to confirm the existence of a continuous wind of atomic particles blowing from the sun, and to map the protective shell of magnetic fields, called the magnetosphere, that envelops the planet. With spaceborne technology, the researchers could even observe the magnetosphere expanding and contracting with solar activity.

Auroral display. Photographed as a polar projection during the end of a magnetic storm, the aurora borealis spans 2,100 kilometers.

Imbrie. Deep-sea cores chart climate.

More recently, scientists have spotted in the sun's atmosphere coronal holes from which emanate high-speed streams of solar particles that sweep at times across the earth like the flow from a garden hose. Guided by the earth's magnetic-field lines, many of the particles are funneled onto the polar regions, affecting both the chemistry and circulation of the atmosphere's topmost layers.

Over these decades of space-based and ground-based explorations, solar-terrestrial physicists have made great advances in understanding the transport of energy from the sun and its absorption by the earth. Their observations indicate that the solar-terrestrial environment is a vital, fluctuating system that can change over time scales ranging from minutes to millennia.

Scientists also realize that the sun's radiation energizes a weather-climate system that is both complex and fragile. If the sun's electromagnetic radiation were to drop by only five to ten percent, for instance, with no compensating changes in carbon-dioxide levels or cloud cover, ice would cover the entire planet in less than a century.

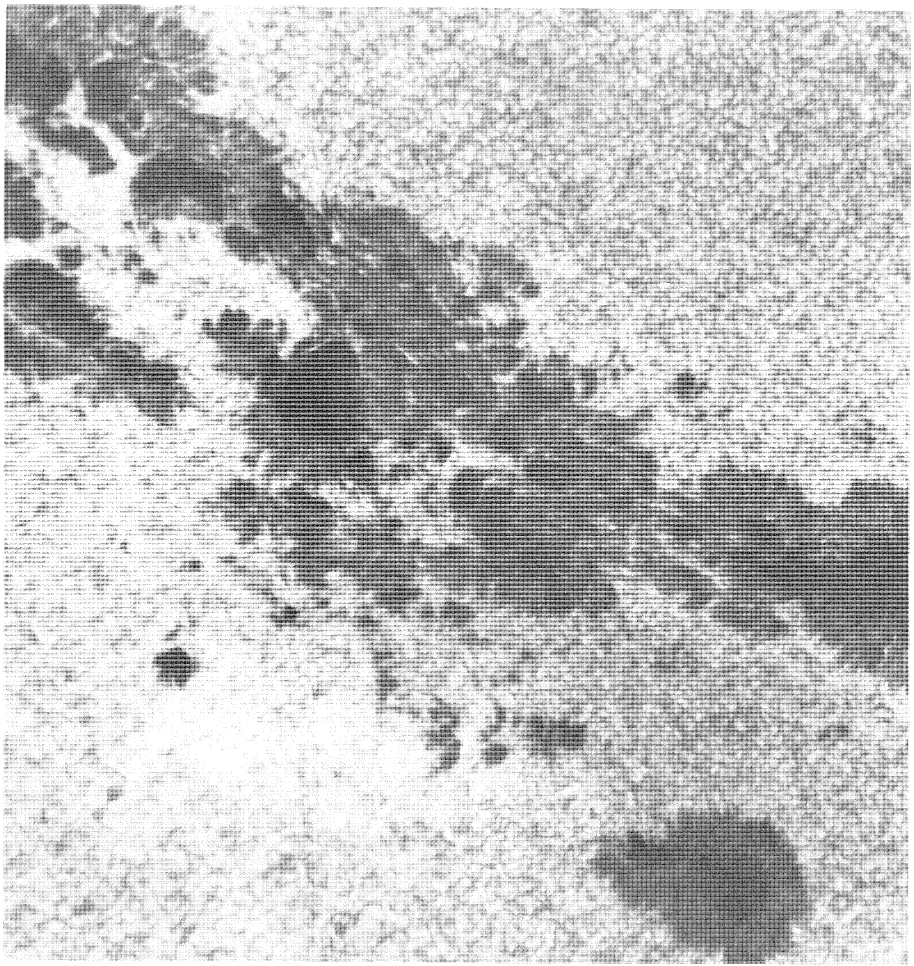
In any study of the earth's relationship to the sun, the ice ages serve as a valuable starting point. These times of repeated glaciation of the earth represent a clear-cut—and more important, a measurable—response of the earth to variations in incoming solar radiation. First recognized by geologists in the late nineteenth century, the ice ages stand out as one of the most dramatic features in the geologic record.

Ice and the orbital dance

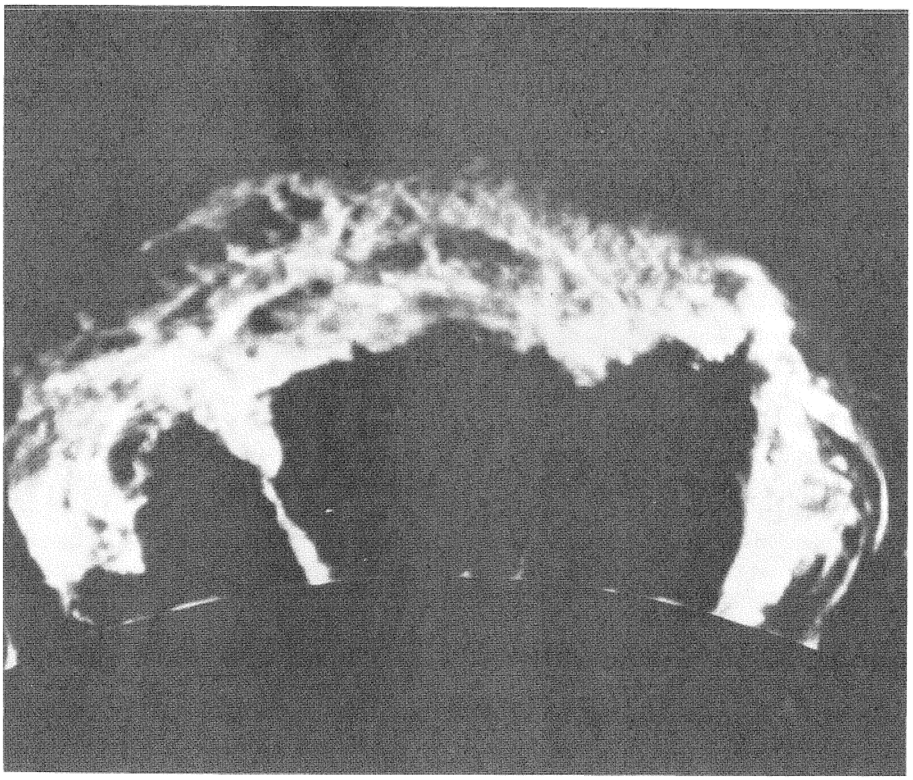
There have been six major ice ages over geologic time: about 2.5 billion years ago, one billion years ago, 700 million years ago, 570 million years ago, 450 million years ago, 300 million years ago, and 1.5 million years ago. Each was marked by repeated advances and retreats of glacial sheets. The most recent one, in the Pleistocene epoch, is the one to which the term "ice age" is most commonly applied.

Over the past million years, the earth has experienced 10 major and 40 minor episodes of glaciation. The most recent cooling reached an extreme some 20,000 years ago, when ice covered Europe as far south as northern Germany and sea levels fell around the world by 100 meters, exposing vast stretches of continental shelf. Glacial sheets two kilometers thick blanketed 28 million square kilometers of North America, Europe, and Asia—areas that today are free of ice. The Pleistocene is considered to have ended with the end some 10,000 years ago of that most recent glacial episode.

In 1864, Scotsman James Croll, who had gone from millwright to insurance salesman to self-taught scientist, suggested that regular, long-term changes in the shape of the earth's orbit might be the cause of the Pleistocene glaciations. Virtually forgotten, Croll's idea was revived in the 1920s by a Serbian mathematician named Milutin Milankovitch, National Optical Astronomy Observatories



Sunspots and eruptions. The eleven-year cycle of sunspots (top) appears to affect weather and related phenomena on earth. A prominence (bottom) erupts from the sun's surface.



who quantified the effect more rigorously after spending years painstakingly calculating the distribution of the sun's radiation over the earth's surface. Milankovitch particularly argued that less solar radiation in high latitudes during the summer months had been critical to continental glaciation.

Other scientists pointed to the fact that the sunlight falling on the earth over a year's time would vary by only a tiny amount—no more than 0.1 percent—as the earth's orbit changed; too little, they declared, to generate such sweeping climatic changes. As a result, other theories to explain the glacial episodes came into vogue. One posited the periodic passage of the solar system through interstellar dust clouds. Another suggested that the sun might be flickering. Proponents of such theories failed to recognize that a buildup of glacial ice depends more on the way the sunlight is distributed each season—how cold the summers, how warm the winters—than on slight variations in solar radiation received on the earth over a year's time.

By the 1970s, a national effort called CLIMAP, Climate: Long Range Investigations, Mapping, and Prediction, provided the means to test the predictions of the Milankovitch theory with much greater precision than that obtained with geologic records on land. Signs of astronomical influence were sought in a lengthy record of global climate, going back nearly a million years, that CLIMAP researchers extracted from deep-sea cores.

Several notes at once

On the basis of pioneering work by Cesare Emiliani of the University of Miami, geochemists had established by the 1970s that the ratio of two isotopes of oxygen in seawater, oxygen 16 and oxygen 18, fluctuated with the ice ages. When ice sheets formed, more of the heavier isotope, oxygen 18, stayed behind in the ocean, enriching the marine creatures that were later fossilized in deep-sea sediments. Species that flourished in warm water and diminished in colder seas could also be tracked in the cores. "It's like a natural tape-recording system," says climatologist John Imbrie of Brown University.

Deep-sea cores thus became chemical climate charts, displaying over their length the many advances and retreats of the ice sheets. And magnetic reversals, the periodic flips in the polarity of the earth's magnetic field that were recorded in the sediments, at last allowed geologists to date the glaciations fairly precisely. The last flip occurred about 700,000 years ago. (See "When North Becomes South" by Derral Mulholland, *Mosaic* Volume 13 Number 5 September/October 1982.)

What Imbrie and his colleagues, James Hays of the Lamont-Doherty Geological Observatory and Nicholas Shackleton of Cambridge University, discovered in their cores was an irregular series of ups and downs in global climate. A major oscillation occurred roughly every 100,000 years, with minor ones superimposed on that pattern.

"The cycle is not a simple one," says Imbrie. "It's more like a chord on a piano, with several notes being played at once." Applying a technique known as spectral analysis, Imbrie concluded that the notes corresponded very precisely to three orbital phenomena, the same orbital properties that had been elucidated by Milankovitch.

First, there is the systematic change in the earth's tilt. Every 41,000 years, the earth's inclination varies from roughly 22 to 24.5 degrees and back again. An increase in tilt concentrates more of the sun's rays on the poles and concomitantly reduces the amount of radiation received at lower latitudes.

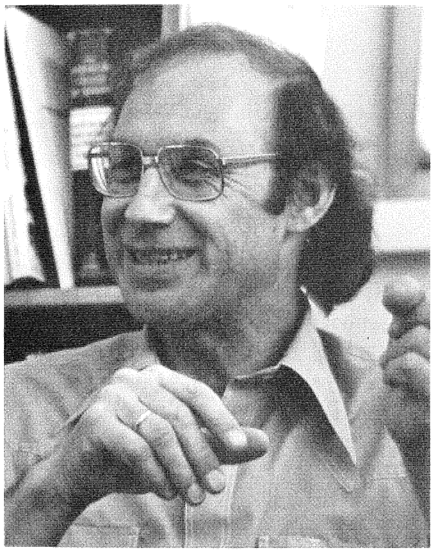
Second, the time at which the earth makes its closest approach to the sun (currently January) slowly changes over a period of 23,000 years. Known as precession, this effect can increase or decrease the intensity of the solar beam by up to 10 percent for a given season and location. A cool summer allows winter snow to persist, causing the polar ice caps to gradually extend.

Third, the shape, or eccentricity, of the earth's orbit regularly changes, with a period of about 100,000 years. Sometimes the orbit is nearly a circle, at other times it is more elliptical. Unlike the other two orbital effects, this factor does change the average yearly amount of solar radiation received at the top of the earth's atmosphere, by some 0.1 to 0.25 percent. The precession effect is also strongest when the orbit is most elliptical.

Pacemakers and amplifiers

Imbrie, Hays, and Shackleton confirmed that these orbital factors are pacemakers of glaciation. Although the combination of precession and axial tilt basically determines when a glacial advance will occur, the eccentricity appears to control the amplitude, or severity, of the climatic shift.

"We identified the external causes, the forcing functions," says Imbrie. "But what we didn't explain were the exact mechanisms by which the earth reacts to these changes in solar irradiance." In fact, trouble arose for the emerging climate model when computer simulations, which mimicked the climatic response to orbital changes, failed to recreate the full intensity of an ice-age swing. But seasonal and latitudinal shifts in solar energy, scientists soon learned, were not the sole controlling factor in the generation of a glacial episode.



Van Loon. Extending sun-earth correlations.

In the early 1980s, French and Swiss scientists analyzed gas bubbles trapped inside ice cores extracted from Antarctica and Greenland. A breakdown of the gases, remnants of Pleistocene atmospheres, demonstrated that carbon-dioxide levels, too, changed as ice sheets expanded and contracted. The amount of carbon dioxide in the atmosphere during the Pleistocene was found to be about 80 parts per million below the levels measured today; this depletion—about 25 percent—probably had the effect of amplifying the cooling initiated by the orbital changes.

Likewise, increases in carbon-dioxide levels, possibly caused by changes in biological activity in the ocean, could account for the rapid melting of glaciers at the end of a glacial interval. Thus, the chemistry of the ocean and atmosphere, as well as variations in orbital geometry, appear to regulate the glacial cycles in some coupled fashion. "This is what global change is all about," says Imbrie, "that the ice sheets, oceans, and plants on land and sea are all linked together."

Seeking mechanisms

The earth's radiation budget is but one strand in the intricate web of global climate. Ice ages themselves are relatively rare—only six over the past 2.5 billion years, three in the past one billion years. The warmer periods between are more likely the earth's norm.

In the millennia before the great Cretaceous-Tertiary extinction some 70 million years ago, for example, dinosaurs were still extant, and the earth was untouched by massive ice sheets. Geologists surmise that the continents, just breaking off from the ancient supercontinent known as Pangea, were in rapid motion, and increased volcanism was releasing more globe-warming carbon dioxide into the atmosphere. Ocean currents might also have been able to warm the globe more efficiently owing to the different continental outlines.

John Imbrie and his colleagues have now entered a new phase in their study of the Milankovitch cycle: a multidisciplinary approach to discerning the physical and chemical mechanisms by which the ocean, coupled with the atmosphere and ice sheets, responds to changes in solar irradiance caused by orbital variations. "The Milankovitch effect is a marvelous opportunity to discover just how sensitive the earth's climate is to a known perturbation, whether man-made or not," says Imbrie. "There are few places in climate studies where you know the exact cause and can then measure the response."

A consortium of geologists, oceanographers, geochemists, and climatologists is attacking this problem on two fronts. Through computer experiments, theorists are asking how changes in radiation and ice volume might alter wind patterns, ocean surface temperatures, and ocean circulation. At the same time, researchers in the field are better documenting the changing carbon budget, as seen through such indicators as levels of calcium carbonate and carbon dioxide in ice and deep-sea sediment cores, to assess the role of biological activity in ice-age development during the Pleistocene.

On the scale of weather

Glacial episodes and the ice ages that spawn them represent a response to extremely long-term variations, from thousands to hundreds of thousands of years, in solar irradiance patterns. More controversial is the question of the earth's reaction to radiative changes of much shorter duration, on the order of days, months, or years.

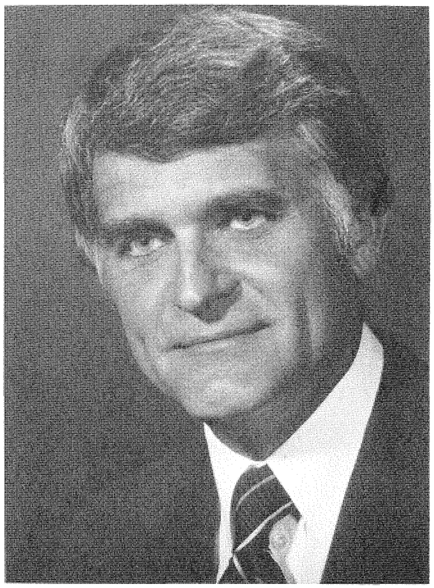
Fascination with a sun-weather link blossomed in the nineteenth century, when scientists first realized that solar flares were somehow connected with stunning auroral displays and that geomagnetic storms could set compass needles spinning wildly. Speculation reached a crescendo in the 1850s when Heinrich Schwabe, a German amateur astronomer, announced that the number of sunspots rose and fell with a period of 11 years. "As soon as scientists recognized that the sun followed an 11-year cycle, it seemed logical to assume that they could find a similar response in the earth's climate," says Jack Eddy. "But they were guided more by hope than by reason." Eddy, a veteran researcher on the sun's past behavior, is the director of the Office for Interdisciplinary Earth Studies, a part of the University Corporation for Atmospheric Research in Boulder, Colorado. (UCAR manages the National Center for Atmospheric Research, NCAR, for the National Science Foundation.)

For decades, various terrestrial phenomena have been grandly touted as following the sun's 11-year cycle; these have included soil temperatures, monsoon patterns, river depths, rainfall, and thunderstorms. The most infamous correlation involved Africa's Lake Victoria, whose waters seemed to rise and fall in perfect synchrony with sunspot counts between 1900 and 1923. Whatever produced the appearance of synchrony, however, it vanished during succeeding years and has not recurred.

"This question is so stimulating that people can't be restrained from going out and attempting to see connections," says Peter Foukal, a solar-terrestrial physicist with Cambridge Research and Instrumentation in Massachusetts. "If a good case could be made for the sun's influence on weather, then that fact alone would be more important than anything else studied in solar-terrestrial physics."

A suggestive link

For many years, the strongest evidence has been a tantalizing link between a series of droughts in the western United States and a solar cycle with a 22-year period, during which the sun's magnetic field switches its polarity. (The sun's magnetic field reverses every 11 years, after a peak of magnetic-storm and sunspot activity; thus, it returns to its original state every 22 years.)



Eddy. Inconsistencies in the solar constant.

More recently, Karin Labitzke of the Free University of Berlin and Harry van Loon at NCAR seem to have connected the 11-year sunspot cycle to more general weather patterns on earth, a discovery that Jack Eddy describes as "the hottest breaking story in the game." The correlations that Labitzke and van Loon uncovered are quite intricate, involving several long-studied phenomena high in the atmosphere above the North Pole and the Equator.

James Holton and H.-C. Tan of the University of Washington, in Seattle, had previously noticed a pole-Equator coincidence. They found that certain wintertime stratospheric winds, blowing from the west, two dozen kilometers over the North Pole, are particularly strong and cold when a stratospheric circulation pattern over the Equator also blows from the west. The equatorial wind reverses direction in a little over a year, with a complete cycle occurring about every 27 months, which is why it is known as the quasi-biennial oscillation, or the QBO.

Labitzke, whose mentor Richard Scherhag had encouraged her to be on the lookout for solar-weather connections, reported in 1982 that the polar-QBO coupling broke down at the time of solar maximum, the peak of the sun's 11-year cycle. Ordinarily, if the QBO were in its west phase, a cold vortex would be expected over the North Pole in wintertime. At solar maximum, however, the polar wind was found instead to be weak and the vortex warm.

It seemed an interesting observation of minor significance, for no pattern was discerned over the solar cycle as a whole. That changed dramatically in 1987, when Labitzke thought to plot the stratospheric wintertime temperatures over the North Pole when the QBO was in its west phase only, ignoring data from the east phase. Immediately, she saw the temperatures 23 kilometers above the pole go up and down in near-perfect step with recorded sunspot counts for three solar cycles. Temperatures were higher when solar activity was high and vortex breakdowns produced an intrusion of warmer air in the arctic stratosphere. They were lower when the sun was quiet.

Labitzke pointed this out to van Loon, who joined her in a more rigorous test of this odd relationship. "When Karin first showed me her data, I suggested we put all our other research aside to concentrate on it," recalls van Loon. "I had never seen a sun-weather signal that I believed in, but this statistical association was too strong to ignore."

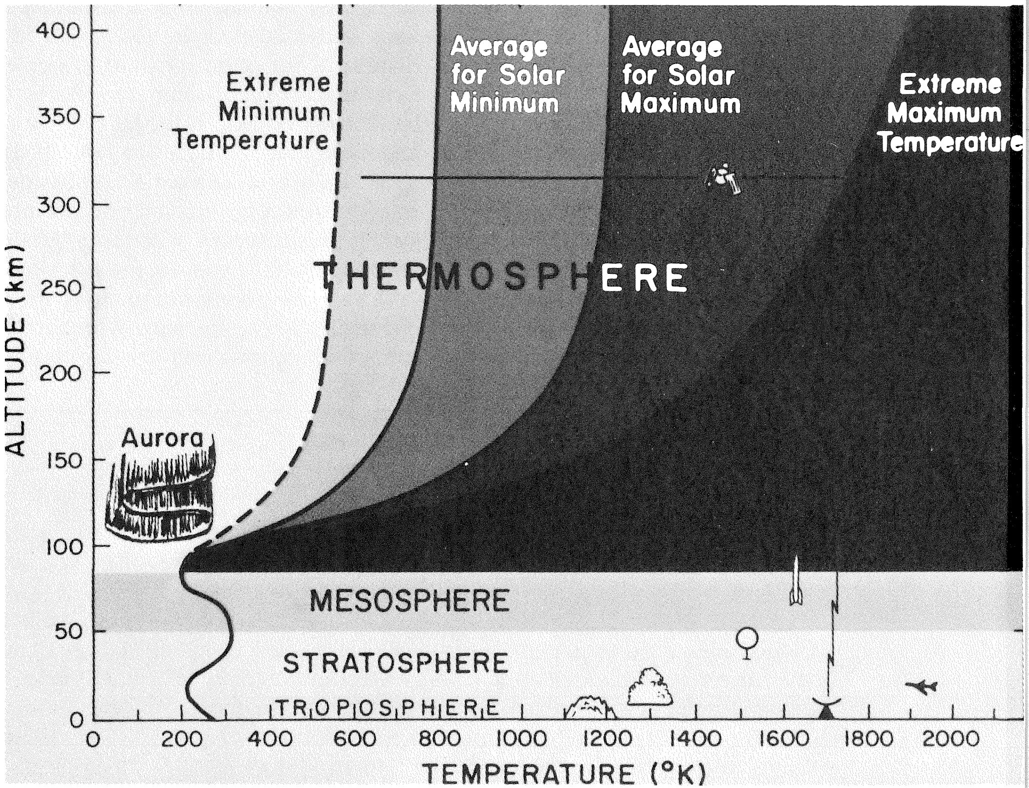
An impressive match

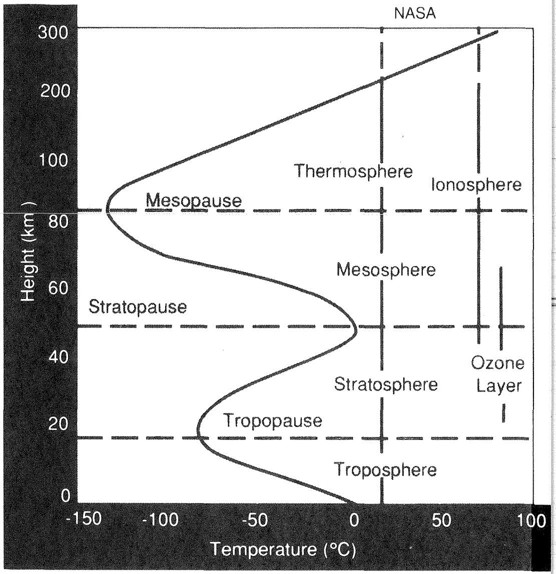
On a scale of zero to one (one being a perfect match), Labitzke and van Loon obtained a correlation coefficient of 0.76—an equivalence rarely seen in sun-weather relationships. It turned out that data during the QBO's east phase were just as intriguing. Stratospheric temperatures over the North Pole and solar activity were anticorrelated with a coefficient of -0.45; polar winters that coincided with an easterly QBO were out of phase with the solar cycle.

Over the next year, Labitzke and van Loon expanded their search both horizontally and vertically, including down into the troposphere. They looked at sea-level atmospheric pressures and temperatures over the whole Northern Hemisphere, with the QBO in both its west and east phases.

The two researchers soon discerned a large area of positive correlation in the troposphere over much of North America, surrounded by areas of negative correlation over the adjacent oceans. When looking at the data collected during the QBO's east phase, they found that these correlations tended to reverse.

Bartusiak writes frequently on physics and the cosmos. Her most recent contribution to Mosaic *was "The High-Energy Universe" in Volume 18 Number 3.*





Temperature profile. Thermosphere and underlying ionosphere (above) are especially susceptible to changes in solar radiation during the sunspot cycle. Layers of earth's atmosphere (right) respond characteristically to the sun's output.

All these findings are supported by noticeable weather effects at selected sites. At times of solar maximum during the QBO's west phase, for example, sea-level air pressure during January and February tends to be high in areas of positive correlation. And when air pressure over North America is high, the clockwise circulation causes the continent's east coast to get more northerly winds. Indeed, in Nashville, Tennessee, at Cape Hatteras on the coast of North Carolina, and in Charleston, South Carolina, recorded wintertime temperatures are lowest at solar maximum during the QBO's west phase. At solar minimum, the pressure and temperature patterns reverse. "It's physically consistent," notes van Loon.

A further confirmation comes from reexamining a study of storm tracks in the North Atlantic Ocean made in the late 1970s by Geoffrey Brown of the University College of Wales and his student Ivor John. Over several successive winters, they found that the average winter storm-track latitude was two to three degrees closer to the equator in years of solar maximum than at solar minimum. By plotting the storm tracks during the west phase of the QBO, aeronomer Brian Tinsley of the University of Texas at Dallas saw that the tracks shift in latitude up to six degrees in synchrony with the solar cycle, with the storm tracks occurring equatorward at solar maximum and poleward at the minimum.

Caveats

Harry van Loon's office walls are currently papered with graphs and maps that are being produced to strengthen the case. Further, according to van Loon, the correlations found in the Northern Hemisphere are being extended with data from the southern half of the globe.

Very aware of the infamous Lake Victoria case (his critics never let him forget it), van Loon is quick to assert two caveats. First, the data go back only to 1952, when QBOs were first observed, which limits the sample to three-and-a-half solar cycles. Second, he and Labitzke can offer no plausible explanation for the strong signal, and neither can anyone else. For just that reason, some scientists are quite wary of this new evidence: How could relatively minute changes on the sun's surface, they ask, affect earthly weather systems so appreciably?

Several years ago, a National Research Council report on solar variability, weather, and climate warned that few answers will arrive until researchers fully understand how the atmosphere works. Continental drift, although an attractive theory for explaining the jigsaw puzzle–like fit of South America and Africa, was virtually ignored until the mechanism—plate tectonics—was revealed. Similarly, a sun-weather link will not be readily accepted until physical processes connecting changes on the sun to changes in the earth's lower atmosphere can be better identified.

This is why interest in the Labitzke-van Loon findings is very high among solar-terrestrial physicists. "We have made an approach to this controversial subject," Labitzke and van Loon reported in the April 1988 *Journal of Atmospheric and Terrestrial Physics*, "which yields results that we believe can be related to features of the circulation of the troposphere and stratosphere and thus open the possibility of physical and dynamical explanation."

The solar constant

According to Jack Eddy, the solar constant—the radiant flux of energy from the sun—is a logical place to begin a search. "The little wiggles in the solar constant exceed by orders of magnitude any other solar influence, including solar flares, coronal transients, or ultraviolet variations," he says. "The simplest solar connection one can think of is the solar constant."

As far back as 1801, William Herschel, court astronomer for King George III of England, suggested that an active sun filled with sunspots was subtly brighter. This, he figured, improved the climate. (As evidence, he contended that the price of wheat went up when sunspots were fewer, allegedly because of the poorer growing conditions). Charles G. Abbot, astrophysicist and secretary of the Smithsonian Institution for a quarter of a century, directed the first systematic measurement of the solar constant. Between 1923 and 1952, daily observations, coordinated by Abbot were made at stations around the world.

More reliable data became available as soon as radiometers were rocketed into space, far above the earth's atmosphere. These satellite observations have at last confirmed that the solar constant, perhaps better labeled the total solar irradiance, is not quite constant; it jiggles. One spaceborne radiometer, designed by Richard Willson at the Jet Propulsion Laboratory and launched in 1980 aboard *Solar Max*, the Solar Maximum Mission's satellite, has registered significant dips, lasting days to weeks, when large groups of sunspots have crossed the sun's face. "We've gone from a situation where no one really knew for sure whether the sun's total output was varying at all—on any time scale—to seeing variations over all time scales from minutes to years," says Peter Foukal.

Herschel now appears to have been quite prescient. Willson and his collaborators reported in 1986 that solar brightness declined by about 0.1 percent from 1980 to 1984, when the sun went from a maximum to a less active mode. Foukal, in collaboration with Judith Lean of the Applied Research Corporation in Maryland, later concurred after comparing data from the *Solar Max* and *Nim-*

Clouds in the climate equations

A complete understanding of the earth's radiation budget, as well as of the way in which energy is absorbed around the globe, will not be achieved until scientists learn more about the most variable parameter in the equations—clouds. "Clouds are not the forgotten objects in climate studies, but they are certainly the neglected ones. We could be off in our assessment of the earth's energy budget by as much as 10 to 20 percent because of our uncertainty in cloud contributions to the planet's total albedo [the measure of its reflectivity]," says National Center for Atmospheric Research scientist James Coakley. "Could we be blowing long-range weather forecasts due to that uncertainty?"

It is well known that carbon dioxide and other trace gases assist in trapping more heat than escapes the earth into space, skewing the delicate balance that keeps the earth's climate in equilibrium. Over the last century, the world has warmed by nearly a degree. "If the rise continues into the twenty-second century," NCAR scientists Robert Dickinson and Ralph Cicerone have reported, "the global average temperature may reach higher values than have occurred in the past ten million years."

Clouds offer the earth a possible escape valve. Atmospheric scientists currently figure that the earth's albedo is around 30 percent, and that roughly three-quarters of that is caused by clouds. What if that fractional contribution were to increase—a conceivable effect as the global climate warms? Theorists surmise that a very small increase in the earth's cloud cover could lead to substantial decreases in global temperatures. A mere 4-percent increase in low-level stratus clouds, for example, could offset the rise of two to three degrees in global temperature produced by a doubling of carbon dioxide.

Unfortunately, these estimates are based on computer models that handle clouds in a very simplistic fashion; real data on cloud cover as it actually occurs are sparse. "Take a trip to the cliffs of Oahu, where masses of air off the Pacific Ocean rush up the precipices and form clouds within a minute," suggests Bruce Barkstrom of the National Aeronautics and Space Administration's Langley Research Center. "Trying to predict where and how that is occurring all over the globe gives you an idea of the unpredictability in this field."

The International Satellite Cloud Climatology Project (ISCCP), currently under way under the aegis of the World Climate Research Program, was organized to acquire a more realistic assessment of global cloud cover. Five geostationary and two polar-orbiting satellites are generating a five-year data set from which more reliable statistics for cloud amounts, types, and heights will be derived.

The questions that ISCCP scientists are asking are very basic ones: How many clouds are truly there? How do they change with the seasons? At the same time, intensive observations of clouds from the ground and the air are being conducted at selected sites as part of a program called FIRE—First International Satellite Cloud Climatology Project Regional Experiment.

Pollution effects

An additional concern is the effect of industrial pollution on clouds. Many scientists believe that clouds, tainted with the trace gases now spewing into the atmosphere, will absorb more solar radiation, which will speed up the global warming trend.

Sean Twomey of the University of Arizona offered a counterargument. Manufactured aerosols, he surmises, would encourage the formation of small water droplets in clouds, as well as increase the total number of water droplets in any one cloud. This, he concludes, would tend to increase a cloud's reflectivity more than it would increase its ability to absorb radiation.

A recent measurement appears to support Twomey's supposition. "It was an accident," recalls James Coakley. "I was in California on sabbatical, looking at satellite cloud images on a computer and hoping to find a way to define cloud edges." Instead, he saw a clear ship trail, the result of stack gases from a ship polluting the overlying clouds in its wake.

By comparing the radiative signal emanating from such ship trails with unpolluted clouds nearby, Coakley and several colleagues concluded that the ship trails had a noticeably higher reflectivity. "This is an important factor in the warming-versus-cooling debate," notes Coakley. Were the increase in manufactured aerosols proportional to the increase in carbon dioxide, it would lead to an *bus 7* radiometers. Variations in the two instruments matched, on time scales ranging from a few months to years.

According to a model developed by Foukal and Lean, faculae—bright solar magnetic regions that pepper the sun's surface and also surround sunspots—play the dominant role in this constant flux. "The excess radiation from the faculae during times of high activity," says Foukal, "outweighs the decrease in radiation caused by dark sunspots." Likewise, a decline in the number of faculae during a solar minimum diminishes total solar irradiance.

Others in the field have been more cautious about this conclusion, since the apparent decline in solar radiation recorded by the radiometers is not much larger than the level of noise in the detectors themselves. Bruce Barkstrom of the National Aeronautics and Space Administration's Langley Research Center, in Virginia, team leader for the Earth Radiation Budget Experiment, which is also tracking the solar constant, notes that "a degradation in the satellite detectors, which might cause the measurements to decrease over time, could be misinterpreted as a change in solar climate."

Preliminary reports, however, are suggesting that the spaceborne detectors are seeing a rise in total solar irradiance as the sun heads back toward its next maximum in 1991. If this finding holds up, it could provide some answers to some longstanding puzzles—such as that of the seventeenth- and eighteenth-


NOAA

Ship trails. In infrared satellite photo, stack-gas trails from ships contrast with nearby unpolluted clouds. The higher reflectivity of polluted clouds could act to offset the greenhouse effect.

appreciable increase in cloud reflectivity, which, if extrapolated over the entire globe, could offset the warming resulting from increased carbon dioxide.

However, there is a catch: Ship trails are created over the ocean, whereas the pollution effect may well be different over land. Soviet scientists flying aircraft over polluted industrial areas even saw cloud reflectivities decline. For a more complete determination, Coakley would like to survey hundreds of square kilometers with satellites.

A complementary approach to determining the role of clouds in the earth's radiation budget is to measure the components of the radiation balance itself—the solar flux coming in and the infrared radiation emitted, in turn, at the top of the earth's atmosphere. Possible changes in this energy balance caused by disruptions in the flow of radiation are the cornerstone of modern climate modeling. The Earth Radiation Budget Experiment (ERBE), now in progress, combines observations from the NASA research satellite ERBS in a low-inclination orbit with measurements from the NOAA *9* and NOAA *10* satellites in polar orbit. The ERBE program represents the most advanced attempt to measure the radiation budget since the beginning of the space age 30 years ago.

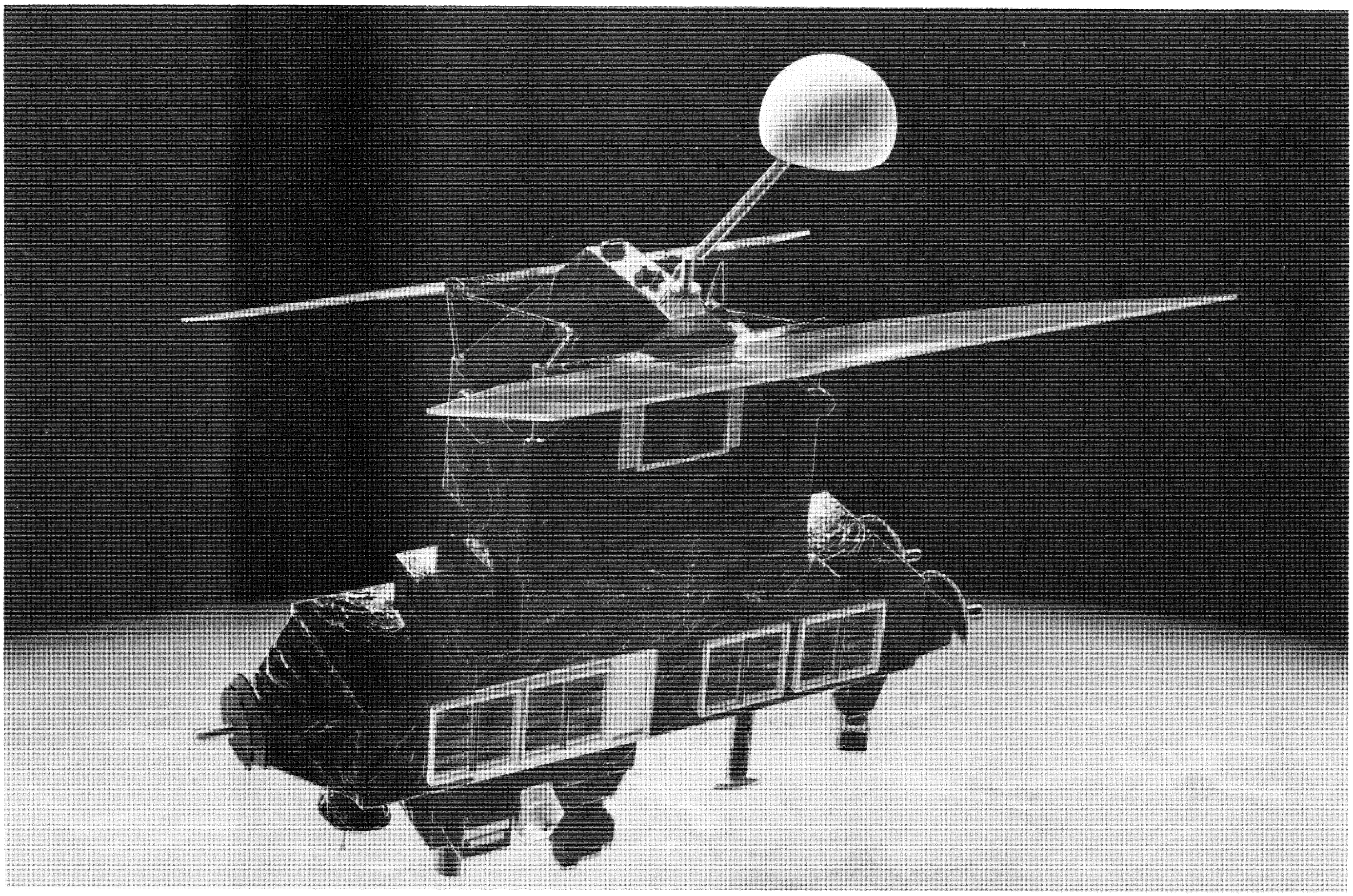
Variables

Through their measurements, the ERBE scientists—an association of NASA, NOAA, and university researchers—are seeing, in a very direct fashion, that both cloud type and height are significant. Low-level clouds emit large amounts of energy into space; clouds at higher altitudes, such as the tops of typhoons and storm cells, on the other hand, emit only half as much.

As Bruce Barkstrom points out, clouds can actually display two opposing effects. They can either reflect shortwave solar radiation back into space, keeping sunlight from being absorbed by the ocean, or they can absorb the longwave radiation the earth emits and thus act as a blanket in warming the surface. "Which wins out?" asks Barkstrom, the ERBE science team leader.

An array of maps from ERBE data, the result of 500,000 lines of code and 200 scientist-years of programming effort at NASA-Langley, are offering some initial clues. Over the oceans, especially off the west coat of South America and over the stormy North Atlantic Ocean, low-level clouds predominate and tend to reflect more radiation than they absorb. Over such regions, the earth experiences a net loss in energy, ranging from 10 to 70 watts per square meter. However, the clouds over desert landscapes tend to be high cirrus and keep heat in.

The ERBE team is far from making any final global assessments. "But," says Barkstrom, "we have a chance now of getting our first handle on cloud-forcing, the net loss and gain of heat from clouds." If low clouds increase appreciably as carbon-dioxide levels rise, a warming trend could be allayed. But if high clouds, such as cirrus or thunderstorms, prevail, then greenhouse heating of the atmosphere could accelerate. ● M. B.



NASA

Eye in the sky. The Earth Radiation Budget Satellite, a space age effort to measure the radiation balance between the earth and the sun.

century deep freeze in Europe and elsewhere called the Little Ice Age.

Current climate models are not much affected by 0.1-percent fluctuations in solar radiation over a ten-year period, although there could be cumulative effects if, for instance, the sun reduces its output by 0.1 percent for several decades.

Starting at the top

The amplitude changes currently observed by the satellite detectors, notes Jack Eddy, are enough to explain the period in history from 1645 to 1715 (the Maunder Sunspot Minimum) when much of the world experienced the coldest decades of the Little Ice Age. There were few sunspots and infrequent auroras at that time, suggesting that solar activity remained at a minimum for some 70 years. Similar periods of quiescent solar activity pepper the geologic records for thousands of years into the past. These events are found in solar-modulated isotopes—carbon 14 and beryllium 10—that are measured in archives such as tree rings and ice cores. The geologic record appears to indicate that the earth's climate has been somehow reacting to these fluctuations in solar energy. The question remains, But how?

Like an onion skin, the earth's atmosphere is composed of separate layers, distinguished by their temperature profiles. In the troposphere, up to 18 kilometers (the bottom layer, where weather largely occurs), temperature decreases with altitude. In the stratosphere, from 18 to 50 kilometers, temperature increases with altitude because of ozone's strong absorption of ultraviolet radiation. In the mesosphere, from 50 to 85 kilometers, temperature again decreases with altitude.

At the top is the thermosphere, from 85 to 100 kilometers above the earth's surface, a layer of rarefied gases that experiences huge fluctuations in temperature and where there is an abundance of atomic species. It is here, in the thermosphere, that auroras deposit their energy and where the ionosphere, a layer of charged particles, is embedded.

"In the case of solar variability and weather, 'where the action is' is surely the upper atmosphere," Jack Eddy observed at a 1982 symposium in Colorado. "It is there that interactions, whatever their importance, must first occur. . . . It is from that point that we can hope to follow them, maybe to disappear and maybe to trigger something as unlikely as once crustal movement was thought to be." Perhaps the effects can be tracked downward, layer by atmospheric layer, to see where the solar energy is lost and to observe how it enters the weather system.

Theorists have not been shy in suggesting possibilities. Some aeronomists have conjectured that geomagnetic storms, with their monstrous electrical potentials, spark atmospheric wave phenomena that filter downward. Others have speculated whether the solar cycle can somehow affect convection near the Equator, producing an effect transmitted out of the tropics by the QBO. Still others have wondered whether increased amounts of ultraviolet radiation hitting the atmosphere during solar maximums might alter the stratospheric ozone layer enough to change heating patterns in the lower atmosphere.

However, critics are quick to point out that ultraviolet radiation from the sun constitutes only a fraction of the energy of visible light. Requiring such radiation to serve as the sun-weather progenitor through its interactions with the topmost layers of the atmosphere may be like asking the bottom of the sea to respond to a fishing line dropped in at the ocean's surface. Yet, nowhere else is the interaction between the sun and the earth seen so clearly—or more strongly.

Thermospheric Weather

"We want to determine the overall weather of the thermosphere," says NCAR senior scientist Robert Dickinson. "How do the sun's rays and particles interact with the separate gases in that region, such as atomic oxygen, molecular oxygen, and molecular nitrogen? How do they respond to geomagnetic storms? And can we find the dynamical means to move those effects to the lower atmosphere?"

Thermospheric weather can be fierce during a geomagnetic storm generated when a surge in the solar wind interacts with the boundary of the earth's magnetosphere and increases the energy deposited into the thermosphere by enhanced auroral activity. Temperatures jump dramatically from readings in the hundreds to readings in the thousands of degrees Kelvin. The chemistry of the thermosphere is significantly altered as hundreds of thousands of megawatts of energy are deposited in the ionosphere. Circulation patterns—normally directed from the Equator to the poles—are reversed.

At solar maximum, extreme ultraviolet radiation and x rays from the sun can increase by a factor of two or three. This is significant because, although visible sunlight passes through the thermosphere largely unaffected, shorter wavelengths interact strongly with the gases in that layer, causing electron and ion densities to increase. The added heating also causes the thermosphere to expand outward from the earth and wind speeds to increase to hundreds of kilometers per hour. "Satellites have been the key to understanding this region," points out Raymond Roble, senior scientist with the High Altitude Observatory at NCAR. "In the 1970s, ground-based instruments only hinted at the global effects now fully measured."

Roble and Dickinson, along with their colleague E. Cicely Ridley, have been modeling this tenuous section of the upper atmosphere on NCAR's *Cray* XMP supercomputer. Starting in the early 1980s, they took the General Circulation Model, long used at NCAR for climate studies, and adapted it for the thermosphere—taking out clouds and mountains and putting in auroras and ionospheric interactions.

With model in hand, Roble and his collaborators, as well as numerous NCAR visiting scientists, have been comparing their theoretical calculations with observations made from ground-based radars, airglow facilities, and NASA's two *Dynamics Explorer* satellites, launched in the early 1980s to monitor the near-space environment. According to Roble, the *Dynamics Explorer* results have shown a rich spectrum of gravity-wave and planetary-scale fluctuations that can now be modeled with increasing realism. "It will be interesting to find out how deep into the atmosphere the solar-terrestrial effects seen in the thermosphere penetrate," he says. "Perhaps we might link it up with what Labitzke and van Loon are seeing below."

Probing the onion layers

Over the last decade, atmospheric scientists have developed robust models of the other atmospheric layers as well. Remote sensing, both from the ground and from space, has further enabled them to verify many of the theoretical predictions. But scientists are beginning to ask how those separate regions are coupled. How are radiative energy, momentum, and mass transferred from one region of the atmosphere to the next?

A program called CEDAR—Coupling, Energetics, and Dynamics of Atmospheric Regions—has been established as part of the National Science Foundation's global geosciences initiative to address this need. With CEDAR, studies of the mean state of the thermosphere and ionosphere, using ground-based instruments, will be conducted throughout most of the coming decade. The instruments will include spectrometers, interferometers, lidar, radar, and optical imaging devices.

A parallel effort will be conducted to interpret the data through theoretical modeling. "Previous to CEDAR," says Roble, "research was conducted at individual stations. Data were sparse—a rocket measurement here, another over there, but no continuous record. Now we're attempting to obtain a global picture by coordinating measurements in organized campaigns." How is the atmosphere responding as a whole, they are beginning to ask, throughout an entire solar cycle?

Particular attention will be paid to the mesosphere—"the last frontier," as Roble calls it, because it has not been as fully explored as the other atmospheric regions. It is there that various wave motions, such as planetary waves, atmospheric gravity waves, and tides serve to transport energy and chemicals both horizontally and vertically. It is recognized that mesospheric-thermospheric coupling and dynamics significantly influence the structure, composition, and chemistry of lower altitudes. With CEDAR, researchers hope to understand more fully the role of the upper atmosphere as both absorber and transporter of solar energy.

A note of irony

In the 1970s, researchers confirmed that changes in the earth's orbit and tilt, which affect solar radiation patterns, were the major impetus of the ice ages. With the 1980s, scientists may have achieved a breakthrough in linking cyclical changes on the sun to terrestrial weather events, although the mechanism is far from known. Yet the effects of human activity are swiftly changing all the rules. One of the world's most reliable diaries of solar change—carbon 14 in tree rings—has become garbled owing to the injection of carbon dioxide into the atmosphere since the start of the Industrial Revolution. This makes it more and more difficult to distinguish the solar effects on climate from the anthropogenic. "Greenhouse-related climate changes will likely dwarf any effects from solar-output variations," says Robert Dickinson.

While variations in the earth's orbit and tilt are the pacemakers with regard to climate, trace gases are surely the regulators, and they are warping the climate from its natural equilibrium position. During the Little Ice Age, global temperatures dropped by about 0.4 degree Celsius, but during the last century the industrial earth has already warmed by more than half a degree.

Over the next 20,000 years, the earth should be headed for a new ice age, according to the Milankovitch cycle. But will that cooling trend be delayed or canceled altogether?

It is an ironic twist to this scientific venture: Human activity is becoming more of a lever on climate changes than changes in the sun itself. People in the twentieth century, on the verge of understanding the sun-earth connection, may jumble the answer before it can be comprehended. ●