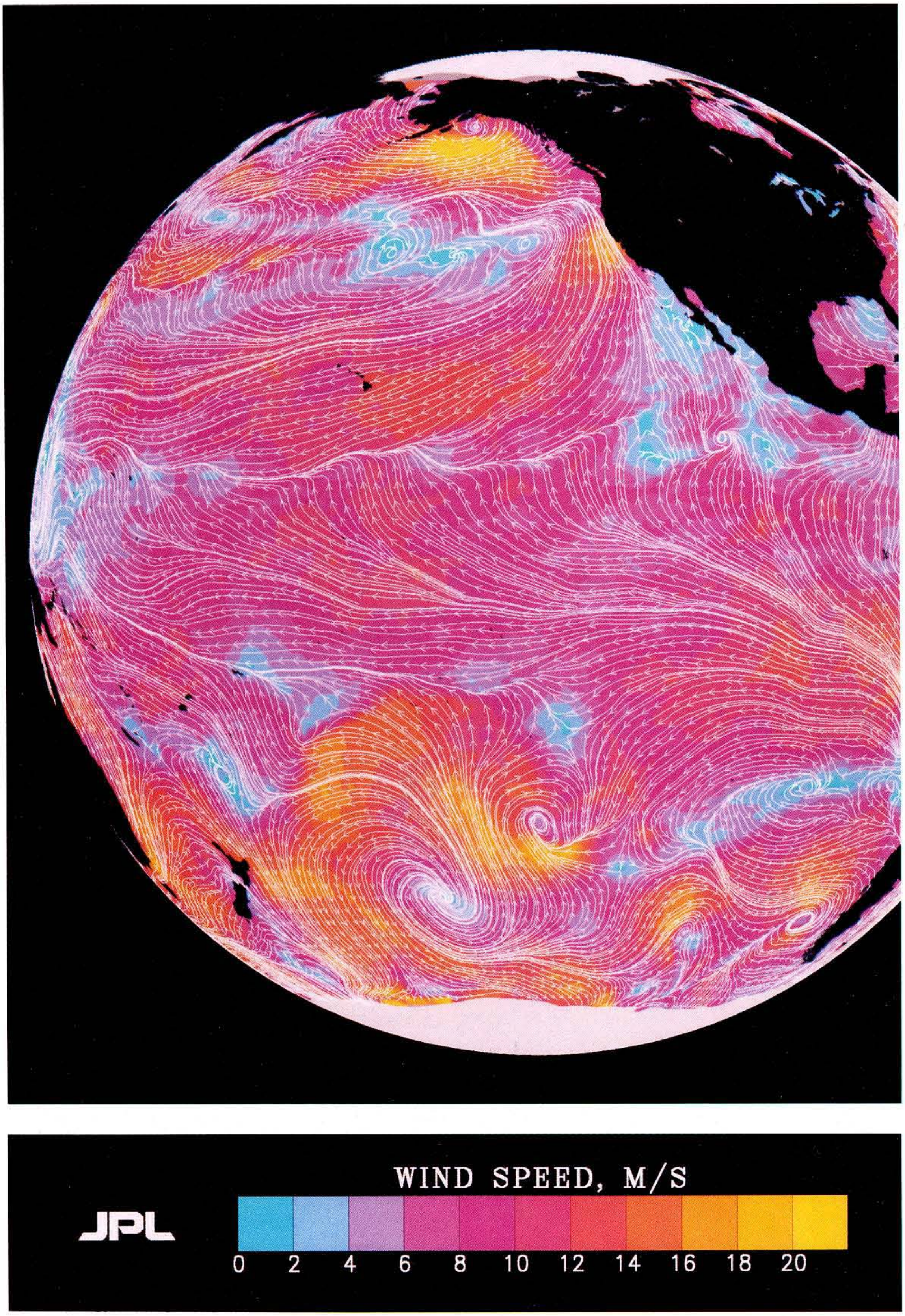
WIND SPEED, M/S
JPL
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Observing Earth From Space: The Greenhouse Effect

Surface winds on September 17, 1978, as measured by NASA's SEASAT scatterometer. Arrows show wind direction, colors indicate speed. Converging white lines generally correspond to cloud bands in weather photo opposite. Storms (counterclockwise swirls in the Northern Hemisphere, clockwise in the Southern) are visible off Alaska, Mexico, Chile, and in the mid–South Pacific. High-pressure regions (which swirl opposite to storms in each hemisphere) appear between Alaska and Hawaii, and north and east of New Zealand. Data from 7 orbits spanning 12 hours were interpolated and time-corrected to show the entire Pacific at 1800 hours Greenwich Mean Time. The meteorological analysis needed to produce this image was performed jointly by JPL, UCLA, and AES-Canada.

"Most scientists have always looked at the earth, our planet, through the eyes of their particular discipline—geology, oceanography, biology, or whatever," says Moustafa T. Chahine, Chief Scientist at Caltech's Jet Propulsion Laboratory. "But planetary exploration scientists are used to looking at planets as unified systems: Mars is polar caps and wind and dust storms all rolled together. This is just now happening in earth sciences, as the problems we face become more complex and interdependent."

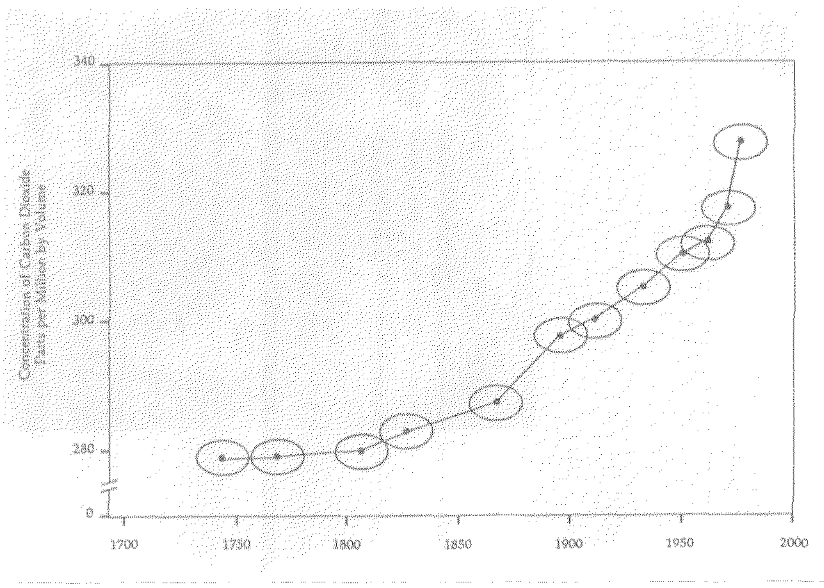
A case in point is the likely acceleration of the greenhouse effect—the predicted speedup of a process that naturally warms the earth's atmosphere. "Greenhouse gases" are transparent to visible light: like panes of glass in a greenhouse, they allow sunlight to warm the earth's surface but absorb the infrared (thermal) radiation given off by the warmed earth, keeping the heat trapped in the atmosphere. If the process went unchecked, it would change our climate on a planetary scale, but the greenhouse gases have been in equilibrium with the rest of the atmosphere until now. Man is pumping greenhouse gases into the atmosphere faster than nature removes them—carbon dioxide from burning fossil fuels (and from slash-and-burn farming, still practiced in parts of the Third World), chlorofluorocarbons from air conditioners and refrigerators, and methane from agriculture.

If these emissions continue at their present rate, computerized climate models predict that the earth could be an average of 3°C warmer by 2100. This hardly sounds like cause for alarm, but it means, among other things, a 100-foot rise in sea level. Richmond, Virginia, and Orlando, Florida, would become beachfront property, and much of New Jersey would only be visible at low tide. (Caltech, at about 765 feet above sea level, would still be on dry land.) Rainfall and vegetation patterns would change, making much of the Midwest a desert and shifting the grain belt north to Canada.

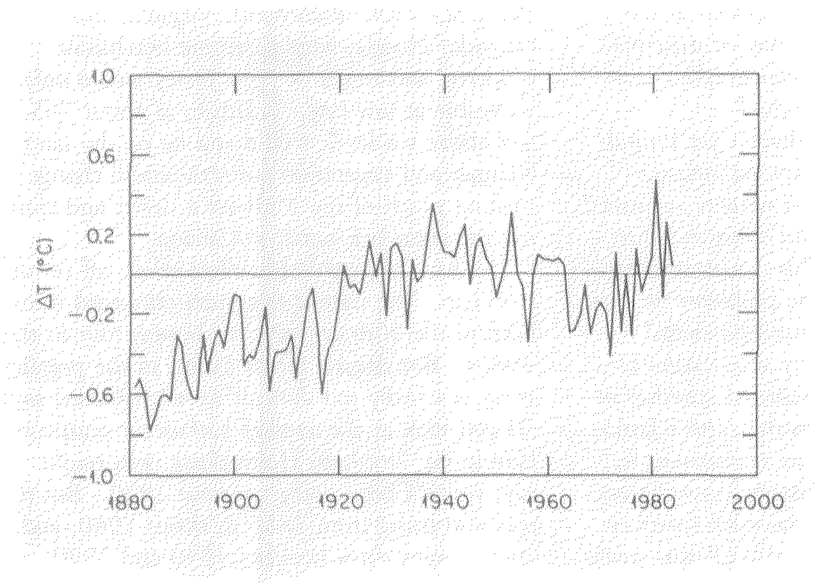
So has the greenhouse effect taken off yet or hasn't it? The hottest five years on record have been in the 20th century, the hottest four in the 1980s. But despite recent claims in the popular press, it's really too difficult to tell, Chahine says. "If you look at the average surface air temperature in the Northern Hemisphere, you might say, yes, it's been going up since 1970. But it was also rising from 1880 to about 1940, and then it went *down* between 1940 and 1970. Atmospheric CO_2 has been accumulating steadily since 1865, so why don't the temperature data match?"

The snag, according to Chahine, is that the onset of increased greenhouse warming will be very subtle. Global average temperature will climb less than one-tenth of a degree Centigrade per year, superimposed on background fluctuations of many times that amount. "Suppose the CO_2-related warming is superimposed on another warming–cooling cycle that's out of phase. The two will cancel each other for a while, but then they'll come back into phase and the temperature will suddenly take off."

Over the last 40,000 years, the earth's average temperature has fluctuated over a range of about 8°C, as recorded in the relative abundance



"It's like being a doctor before the days of x rays and CAT scans. . . . We could take the pulse, and listen to the heartbeat, but we really didn't know what was going on inside the body."

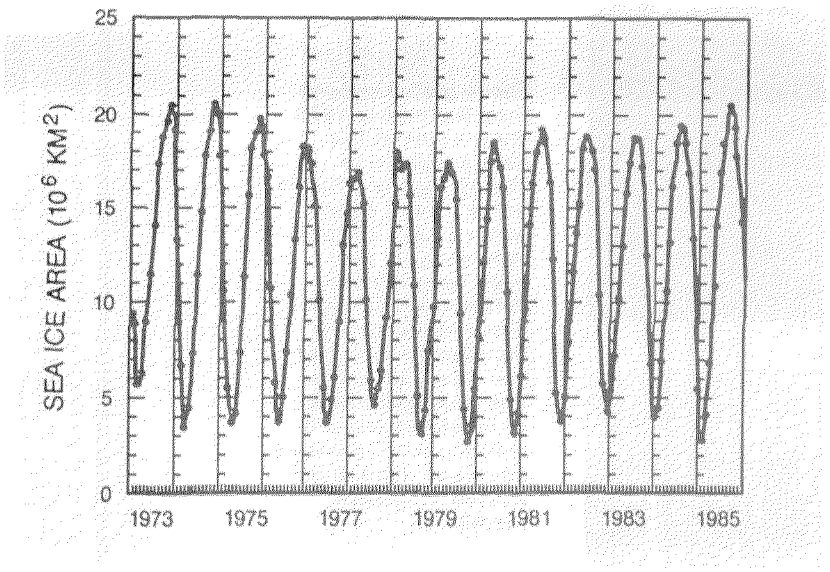


Top: Atmospheric CO_2 concentrations have increased steadily since 1865, as estimated from glacier ice cores. [Neftel et al., 1985]
Bottom: Changes in annual average surface air temperature for the Northern Hemisphere. [Wigley et al., 1984]

of shells from cold-water-dwelling foraminifera in deep-sea sediment cores taken west of the British Isles. And the changes have been abrupt, not gradual. About 15,000 years ago, the ocean warmed dramatically and has stayed warm ever since, except for two intensely cold periods of a few hundred years' duration each. So there have been cycles within cycles: hundred-year chills in a 15,000-year warming trend. But what's 15,000 out of 4.5 billion years? Are there still larger cycles undiscovered?

This leads to a related difficulty: the lack of a sufficiently accurate long-term baseline against which to compare today's measurements. Thermometers didn't come into use until after 1700, and much of the early data is of little value, due to difficulties in constructing accurate thermometers. But even if one takes the data from a given city since 1880, for example, and corrects for the different methods and instruments then in use, other subtle effects remain. Has the observing station been moved? Did what used to be a shady grove of trees become a sun-drenched rooftop, or an ovenlike asphalt parking lot?

But the central difficulty, Chahine says, is that "the problem is too big for our computer models, and many of the correlations and feedback processes aren't known. Everything is interrelated. Photosynthesis in trees is one of the primary ways to get carbon dioxide out of the atmosphere, by converting it into wood. So deforestation contributes to CO_2 buildup in two ways, by killing the tree and burning its wood. If the CO_2 level increases enough to melt some polar ice, the sea level rises. The smaller polar



Unfortunately, many of the observable effects aren't all that observable.

Sea ice in the Antarctic fluctuates in an annual cycle, with no apparent long-term trends. [Zwally et al., 1986]

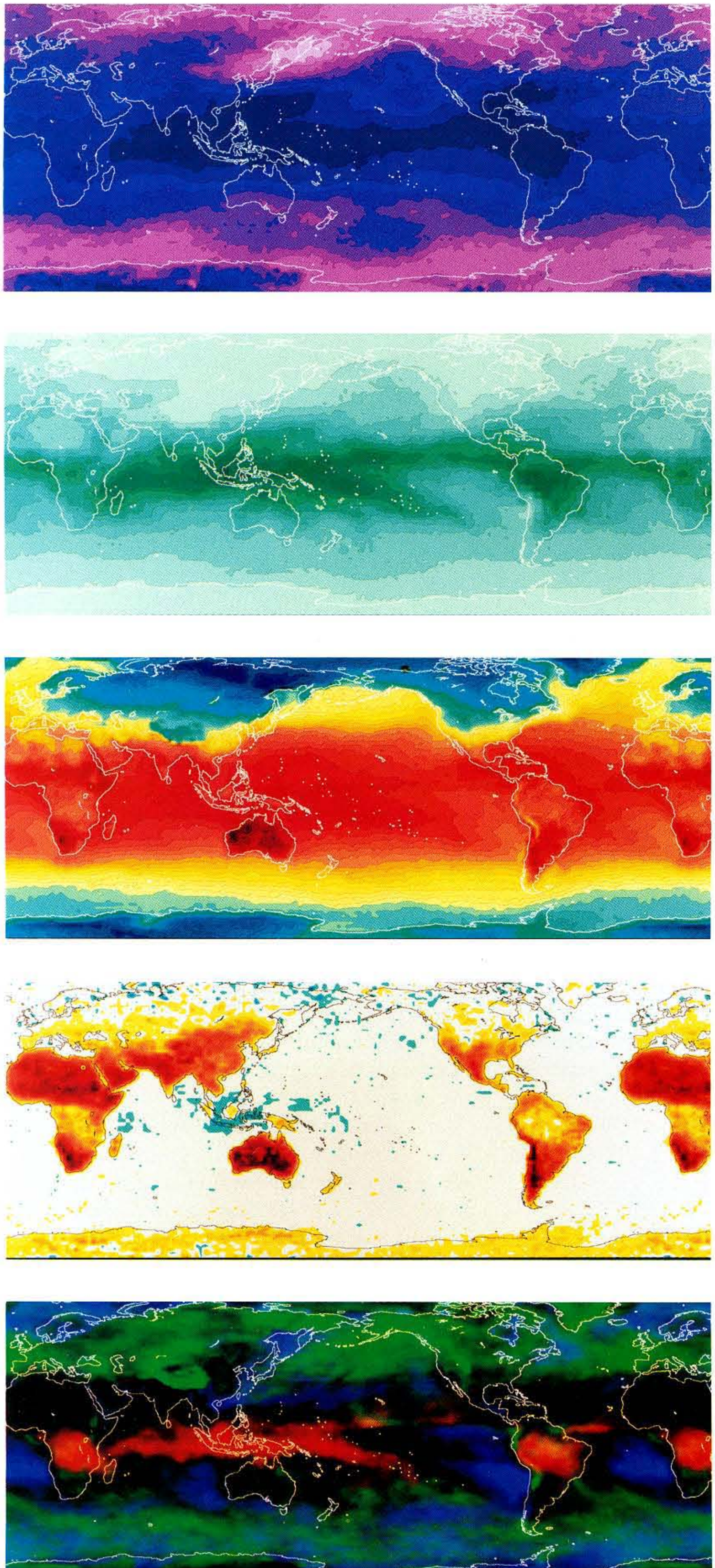
caps will reflect less sunlight back into space, amplifying the warming trend. But as the climate warms, there will be more evaporation from the oceans, and hence more cloud cover, and thus less sunlight warming the earth's surface. Which effects will predominate? No one knows. The air–surface interactions for the ocean have been modeled, for example, but the land really hasn't—it's too varied. The topography changes, the vegetation changes, heat capacity, albedo, everything varies. The oceans are much more homogeneous. A few variables suffice to describe most things. It's like being a doctor before the days of x rays and CAT scans and all these other diagnostic tools. We could take the pulse, and listen to the heartbeat, but we didn't really know what was going on inside the body."

But some of the correlations are known, and should have observable effects. "There are several different witnesses that can testify about increased global warming, so let's call the next witness." Polar cap size, and global snow and ice coverage, should shrink as the earth warms. So far this hasn't happened. Ditto for the predicted sea-level rise. The stratosphere should begin to cool, oddly enough, and this is, in fact, happening.

Unfortunately, many of the observable effects aren't all that observable. The required instruments either aren't in orbit (or are in the wrong orbit for global coverage), or weren't designed for this particular task. Global cloud cover should increase, for example, but current satellite data are only accurate to ± 5 percent, and a mere 1 percent more cloudiness would nullify the current rate of increase of CO_2 concentration. Data accurate to better than 1 percent are needed. Rainfall patterns and the global moisture balance should change. These two items can be measured at ground stations, but there is no instrument in orbit today that can track these changes worldwide. (Furthermore, ground stations tend to be on land, but much of the data needed for the model must come from the oceans.) Atmospheric moisture data are incomplete, and are subject to sizeable errors in certain regions. Weather satellites record cloud cover around the world, but they don't provide detailed enough data. Wind data are not available for the whole planet, and what is available is of dubious accuracy. Nor is there any instrument aloft that can measure moisture in the soil. Vegetation distribution will change, and progress is being made in correlating ground-based plant inventories with satellite data, but much basic research needs to be done on the "inversion algorithms" that translate figures into fauna.

Not only are there several witnesses, but there is more than one defendant as well. Warming could be due to increased solar output, or to a change in the earth's albedo (the way it reflects light) or in the amount of aerosols in the atmosphere. Each of these defendants has its own set of correlations. But again, the testimony is inconclusive. The jury's still out.

"Our climate is a non-linear system with a large number of feedbacks," says Chahine. "It makes linear thinking impossible. The climate system will stay put at one spot for a long time,

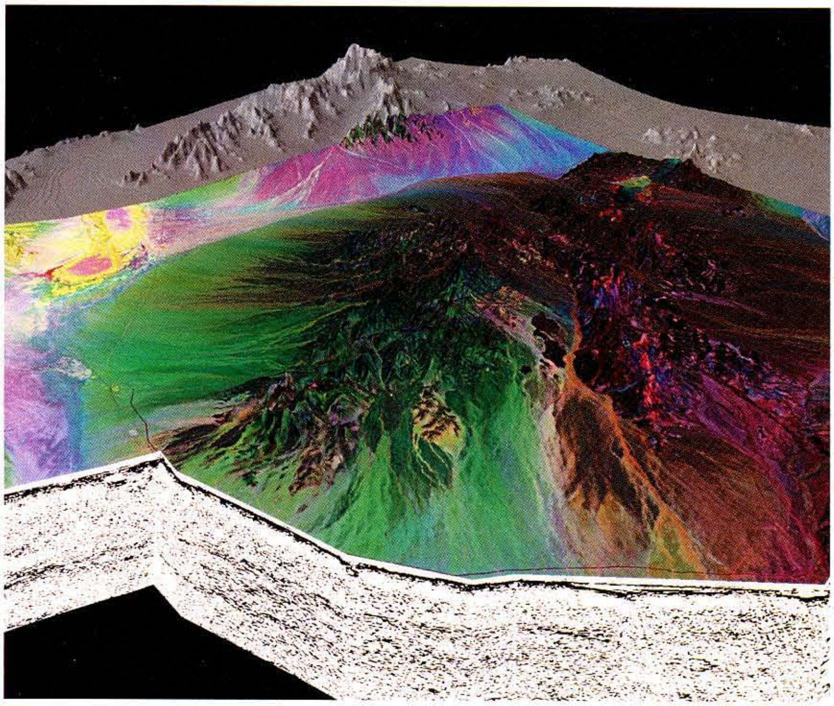


These global images from December 1978 show some of the data available to climatologists. Top to bottom: total ozone; water vapor; surface temperature; day/night temperature difference; and cloud cover at high (red), medium (green), and low (blue) altitudes. The next generation of satellites will provide the more detailed coverage needed for accurate climate modeling.

even though you're continually changing the input. Then it will suddenly change radically, leaping to a new quasi-stable state. It's like your body weight. You can eat everything in sight and nothing happens. Then you eat an ice cream cone and suddenly gain two pounds. Furthermore, climate models show what we call 'chaotic behavior.' If you start two computer simulations with almost identical initial conditions, they rapidly diverge to the point where they don't resemble each other at all."

There are two conclusions to be drawn. First, if we continue our present course, increased warming *is* coming. Carbon dioxide is increasing at the rate of 0.4 percent per year and, once in the atmosphere, each molecule stays there an average of 2 to 3 years. Methane is increasing at 1.1 percent per year, with a residence time of 11 years. Nitrous oxide (N_2O, emitted by nitrogen-based fertilizers, and by burning fossil fuels) is only increasing at 0.2 percent annually, but each molecule lingers on for an average of 150 years. So it's only a matter of time. Second, we will not know at the time the effect starts that it has, in fact, begun. The data are too fuzzy; the masking effects are too strong. The best we may be able to do is to look at the data several decades hence and say, "Ah, yes. The warming trend began back here."

But just because we can't see it yet doesn't mean there's time to waste, Chahine says. "We have got to protect our tropical forests. They are our first line of defense to get CO_2 out of the atmosphere. We need to stop using freons. We need to conserve energy, so that we get more



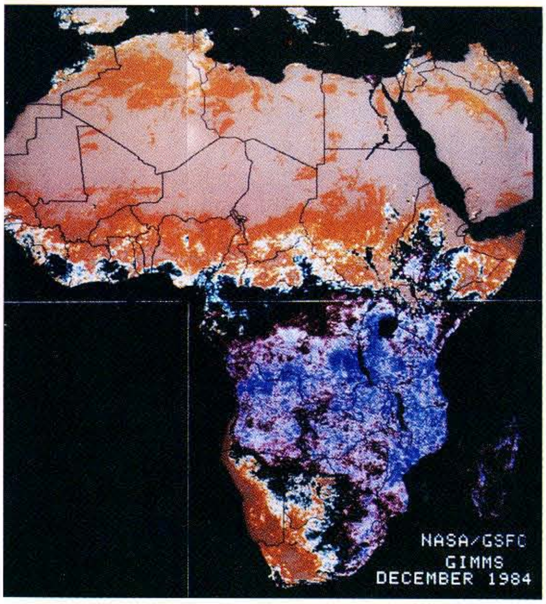
Left: This 3-D view of California's Turtle Mountains combines satellite and ground-based data—elevation data from the Shuttle Imaging Radar, false-color visible and near-infrared spectral data from the LANDSAT Thematic Mapper, and a seismic-reflection profile from CALCRUST showing subsurface features (white band at bottom). Colors reflect surface mineralogy and vegetation. Ferric iron is blue; ferrous iron, green; clays, carbonates, and vegetation are red. The area shown is about 50 km square.

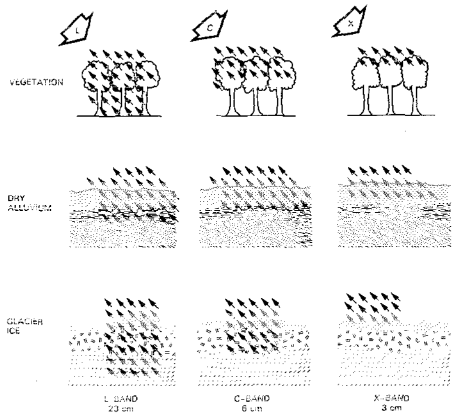
Below: Vegetation distribution in Africa from spectral analysis of light reflected from leaves. Desert is tan, grasslands are yellow and light green, woodlands (including rain forest and jungle) are dark green, red, and dark blue.

efficient use of the energy we do consume. And we have to start using cleaner fuels—natural gas instead of coal, for example—and we should move to nonfossil fuels such as solar energy as fast as possible. We have started on some of these things, but there is a long way to go on all of them. If we stopped emitting CO_2 today, and stopped cutting down forests, the damage we've already done would linger for a century, just because of the residence time of the gases."

"We have got to protect our tropical forests. They are our first line of defense."

We're not likely to stop chopping down trees tomorrow, much less quit burning coal and gasoline, so Chahine suggests a stopgap measure. "We should make a worldwide agreement to limit the man-made temperature rise to 1°C per century—0.1° per decade. [It could be 3°C hotter by 2100 otherwise.] I hope that 100 years would buy us enough time to learn how the climate system works, and how to undo the damage we have already done before it's too late." But to make such an agreement, we would need to determine what combination of activities would be tolerable under that level of increase, and how they would be distributed. How many tons of coal would the U.S. be allowed to burn per year? How many acres of rain forest could Brazil clear? Perhaps credits could be traded between nations—the U.S. might be allowed to burn an additional million tons of coal for every thousand acres of trees it planted in Brazil, for example. "Can we model our climate in such a way to specify how much greenhouse gas would limit the temperature rise to one degree? Not yet. Or if we set arbitrary limits, will we have enough data to know if





Microwave radars penetrate to different depths, depending on the wavelength.

"We should make a world-wide agreement to limit the man-made temperature rise to 1°C per century."

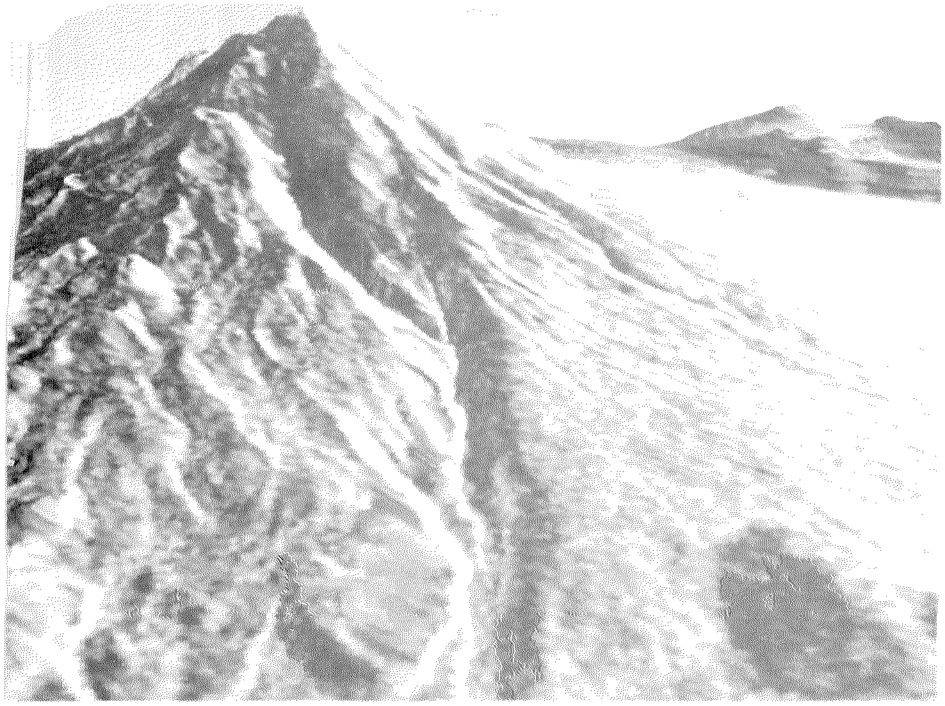
they're working? No. But we have to start somewhere. And I think this agreement would show that there's hope—that we'll be able to work together to solve the problem. The political ramifications would be great. It would change how nations deal with each other—forcing a depth of collaboration we have never tried before. Energy has been the foundation of civilization ever since the discovery of fire, and now we will have to put controls on its use. But I think a 1°C limit would be easier to work with than an attempt to cut all emissions by a set amount, because it has more flexibility to accommodate different needs. And I think people will accept that 1°C is a reasonable place to start until we know better."

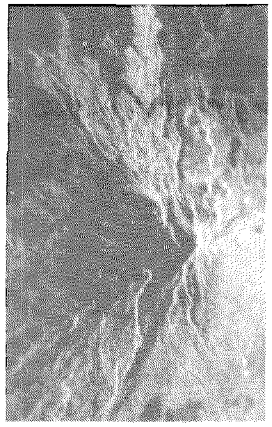
An international movement to address planetary environmental problems is taking shape. Officials from the national space agencies of Austria, Belgium, Brazil, Canada, China, France, Great Britain, Italy, Japan, the Netherlands, Norway, the Soviet Union, Sweden, the U.S., and West Germany met in April 1988 to design a Mission to Planet Earth as part of the International Space Year (ISY). Slated for 1992, the 500th anniversary of Columbus's discovery of the New World, the ISY will pool the resources of the spacefaring nations to begin a new era of exploration.

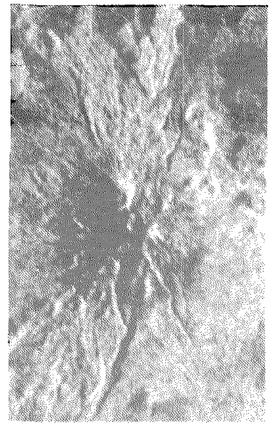
The Mission to Planet Earth will apply these resources to two specific projects—the detection of global and regional change due to an enhanced greenhouse effect, and monitoring the spread of deforestation. Says Chahine, "The ISY is only a start, a test case to see if we can take the pulse of the planet. It is the beginning of what must be done to solve the problem. Could the U.S. or JPL then propose a scheme where a one-degree limit would work? I don't know."

The greenhouse project, according to their report, will "require creating global datasets of atmospheric temperature, pressure, humidity, and wind velocity, both near the surface and throughout the atmosphere. Any long-term trends thus established will be compared against other indicators of global change, such as changing rainfall patterns, changing ecosystem patterns, changing oceanic cloud cover due to increasing sea-surface temperatures, polar warming and its consequences for permafrost and snow distribution and global sea-ice volume, stratospheric temperature changes, and coastal inundation." By collating all of this information, they hope to provide a mass of evidence sufficient to sway the jury one way or the other.

The mission's broader goal is to integrate the welter of satellite data, along with ground-based, airborne, and archived data, into a single "encyclopedia of the earth" that will be available to all researchers. The encyclopedia will serve as a baseline against which global changes, including greenhouse warming, can be measured. More importantly, using this detailed body of localized data in climate models instead of the world-wide-averaged data currently in use will make the models more sensitive, highlighting critical regional differences instead of obscuring them. The encyclopedia would also aid researchers working on more regional problems such as deforestation, desertification, acid rain, and







This 3-D view of Mt. Shasta was created from a pair of Shuttle Imaging Radar images taken at 29° from vertical (right) and 60° from vertical (far right).

the effects of air and water pollution.

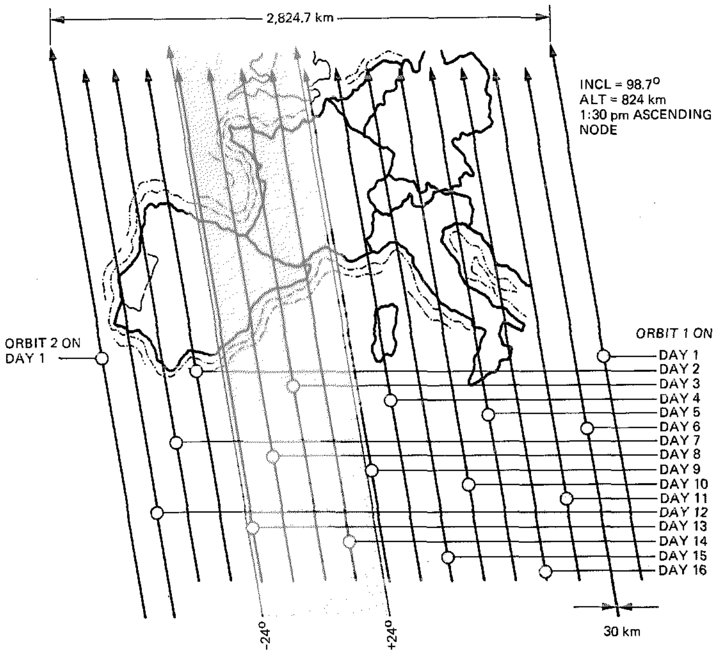
As a first step in that direction, the ISY committee circulated a questionnaire, asking the respondents to list their current and planned spaceborne instruments, along with such other pertinent information as the launch date, orbital trajectory, and sensor capabilities. This inventory will be circulated worldwide, and will be updated periodically. The inventory will allow planners to find where gaps in the current coverage exist, with an eye to filling those gaps with future launches.

This will be followed by a "global change directory"—a database, in a standardized, network-accessible format, of all satellite datasets available. The directory would include the satellite and sensor, areas and wavelengths covered, dates of coverage, data format, archive location and contact person, and so forth—the index volume to the encyclopedia of the earth, in other words.

A number of new satellites should be in orbit, or ready for launch, in time for the ISY. These will include TOPEX/Poseidon (a joint venture of the United States and France, to be managed by JPL), and NASA's Upper Atmosphere Research Satellite (UARS), as well as the European Space Agency's Earth Resources Satellite (ERS-1), and perhaps Japan's JERS-1. TOPEX/Poseidon will be able to make more accurate measurements of sea level, and will map surface ocean currents. UARS will take the first comprehensive look at the stratosphere's composition and dynamics. ERS-1 will have a scatterometer to determine wind stresses on the sea's surface, which permit energy transfer between atmosphere and ocean.

The next generation will be NASA's Earth Observing System (EOS) satellites, which grew out of the Earth Systems Science program NASA initiated in 1982. Two satellites are planned, both in polar orbits and carrying complementary instrument loads. Observations will be coordinated between instruments on the two satellites to provide near-simultaneous views of a given feature over a number of spectral regions. Thus correlations can be established for different aspects of a phenomenon studied simultaneously. EOS-1 should blast off in 1996, and will be managed by Goddard Space Flight Center; EOS-2, to be managed by JPL, is slated for launch in 1998. The EOS program is designed to monitor the earth continuously, in unprecedented detail, for at least two complete solar cycles—44 years. (The sun goes through a 22-year cycle of waxing and waning activity. The most visible effect of the solar cycle is the sunspot cycle, but the subtler effects of a brighter or dimmer sun have far-reaching consequences on the earth. It will take a couple of cycles' worth of data to sort them out.)

Forty-four years is probably longer than the lifetime of a single spacecraft, so maintaining continuity in the observations is a formidable task. One method under consideration is redundancy, i.e., placing duplicate instruments on board, but this runs into difficulty due to the great size and weight of some of the instruments. Another possibility is launching multiple satellites, but this would be expensive, and a delayed



An orbital coverage pattern for HIRIS. Shaded region shows the observable area during Orbit 1, Day 3.

The EOS program is designed to monitor the earth continuously, in unprecedented detail, for at least two complete solar cycles—44 years.

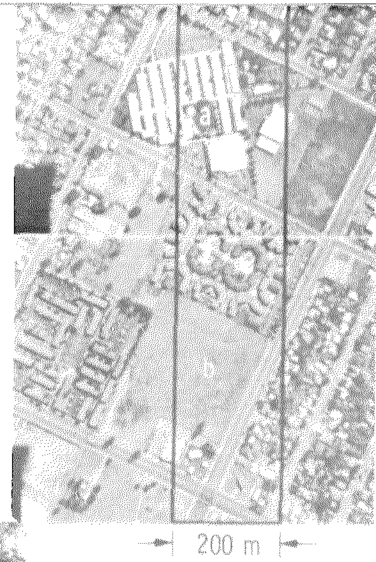
launch could open a gap in the observations. Servicing the satellites in space from a robot vehicle is being considered, but the technical challenges this poses are truly enormous. (EOS couldn't be serviced by Space Shuttle–based astronauts, as the satellites are in polar orbit and the Shuttle is restricted to equatorial flights. Trying to catch the satellite as it crossed the Shuttle's path would be like firing perpendicular rifles 100 yards apart and expecting the bullets to hit each other. Re-orbiting the satellite afterwards would be even tougher.)

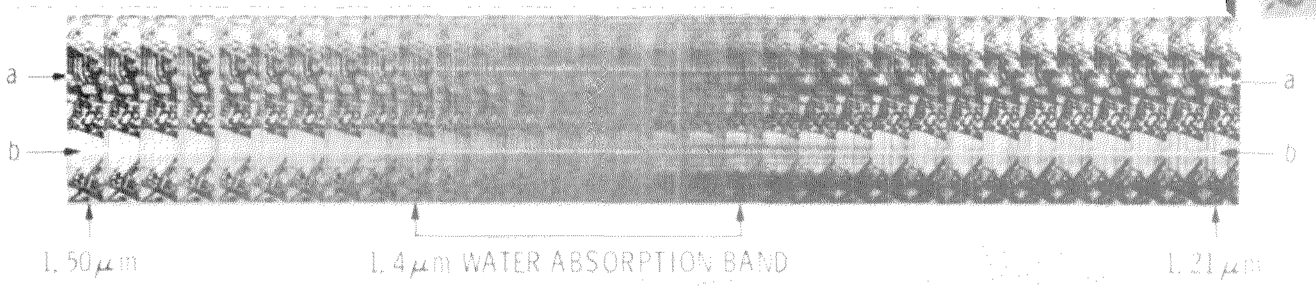
NASA issued the solicitation for EOS's instrument packages and experimental proposals in December, 1987. JPL responded with 16 instrument proposals. "JPL has been developing remote-sensing technologies for missions to other planets for over 25 years," Chahine says. "And we've been applying this expertise to earth since the 1970s. So when the EOS solicitation came out, we had a lot of ideas ready to go." Three of the 16 proposals have been approved as "facility instruments"—instruments available to the scientific community at large, so that any scientist from any institution could submit a proposal and be granted instrument time. Some of the other instruments will be approved as "principal investigator" instruments—designed for a specific experiment by a single scientist, the principal investigator, whose team will operate the instrument and be the primary recipients of its data. The PI instruments are still being chosen, with the selections to be announced in March 1989. In the meantime, prototypes of the facility instruments are being built, and models are being test-flown in aircraft.

Seven facility instruments have been chosen in all. JPL's three are the Atmospheric Infrared Sounder (AIRS), the Synthetic Aperture Radar (SAR), and the High-Resolution Imaging Spectrometer (HIRIS). HIRIS and AIRS will fly on EOS-1, while SAR will take up the bulk of EOS-2. HIRIS will weigh almost a ton, and SAR with its antennas will weigh over two tons. The satellites will be too massive to ride the Space Shuttle, and will be sent into orbit by Titan rockets.

The AIRS will be the lead NASA instrument for greenhouse research. It will give continuous, high-spectral-resolution coverage in the 3- to 17-micron (millionth of a meter) range, the near-infrared portion of the spectrum. AIRS will provide data on atmosphere–ocean coupling—how energy and matter are exchanged between the two bodies. It will study the atmosphere from the boundary layer up. The boundary layer is where the coupling actually occurs, and includes the ocean's "skin" (the topmost micron of water) and the lowest kilometer of air; AIRS will have a unique ability to study it in detail. It will monitor the ocean's (and the land's) surface temperature, the boundary-layer temperature, snow and ice cover, cloud distribution and elevations, and atmospheric humidity and temperature at 1-km vertical intervals up to an altitude of 50 kilometers. AIRS will also map sources of greenhouse gases through trace-gas analysis. This information will help define global energy and water cycles, as well as track climatic variations, and will aid efforts

HIRIS will acquire simultaneous images at 192 wavelengths, ranging from the visible to the near-infrared.



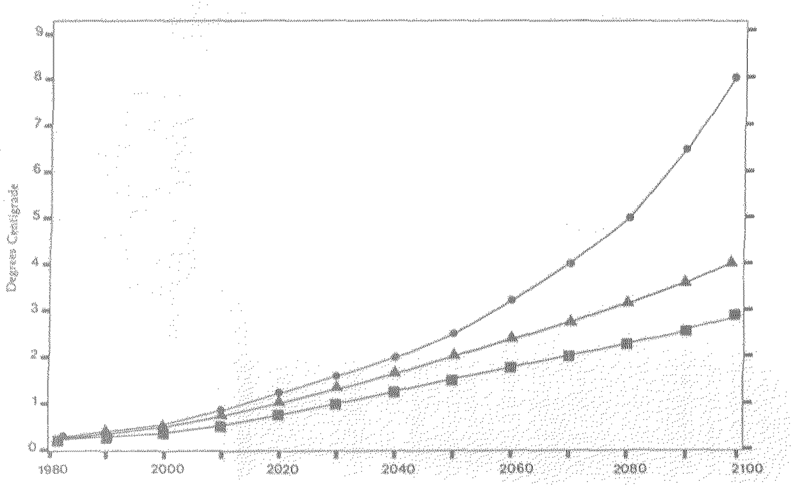


Air photo and spectral image showing (a) a school courtyard and (b) an open field in Van Nuys, California. The black rectangle outlines the area covered at 32 wavelengths between 1.5 and 1.21 microns. The well-watered courtyard shows a different reflectance pattern than the drier field. The gray blur at 1.4 microns is due to atmospheric water vapor.

at numerical weather prediction.

The SAR will map not only the earth's surface, but its vegetative cover and near subsurface (to a depth of 2 to 3 meters—see *E&S*, Sept. '83) as well. Like all radars, the SAR emits a radio beam and measures the portion of the beam reflected by the object being scanned. The SAR will operate on three frequencies in the microwave portion of the spectrum—1.25 GHz (the so-called L-band), 5.3 GHz (the C-band), and 9.6 GHz (the X-band). Microwaves can penetrate an object to some depth before being reflected. Since penetration decreases at higher frequencies, each band provides different information. Thus the L-band can penetrate up to six meters of desert sand. The intermediate C-band reflects strongly from surface features, and the X-band is very sensitive to vegetation. The way a substance reflects microwaves depends on its dielectric constant, which in turn depends on its moisture content. (There is also a marked difference between liquid water and ice.) The SAR will thus be able to map moisture at ground level (in ice and snow as well as standing water), below ground (in soil), and above ground (in leaves). Furthermore, the way in which microwaves scatter off foliage is very sensitive to the geometries of leaves, stems, and trunks. These properties are unique to every species, so it should be possible to identify types of vegetation when views of the same area at different angles and multiple polarizations are compared. SAR's transmitter and detector can be polarized in any direction, and the beam can be aimed to strike the surface at any angle from 15° to 55° from the vertical. Much calibration work remains to be done here, however, with airborne and truck-mounted instruments. The SAR will operate in three modes: a local, high-resolution mode that can resolve features as small as 25 meters over a swath 50 kilometers wide, an intermediate mode, and a global mode that covers the entire planet every three days, offering 500-meter resolution over a 700-km swath. The SAR will be the first orbital imaging radar to provide multifrequency, multipolarization, multiple-incidence-angle observations of the entire earth, and, in its global mode, will provide frequent enough observations to track fast-evolving phenomena like icebergs and volcanoes. It will also provide extensive coverage of the polar icepacks, which have been largely out-of-view to existing instruments.

The HIRIS will acquire simultaneous images at 192 wavelengths, ranging from the visible to the near-infrared portions of the spectrum. The images, taken at 10-nanometer (nm, billionths of a meter) intervals from 0.4 to 2.5 microns, extract virtually all the information contained in the incident light, and much more information than any other sensor yet envisioned. With a 30-meter resolution (the same as LANDSAT's) over a 30-km swath and the capacity to aim from +60° to −30° along its track and ±24° across its track, HIRIS is designed to zero in on specific sites rather than to map large areas. EOS-2's polar orbit will bring HIRIS back over the same spot every 16 days, but its ability to look sideways means it will be able to observe any given point more frequently than that—from every 3 to 4 days for a site at 40° north or south



Predicted surface warming effects if present emission trends continue. Squares = CO_2 + N_2O + CH_4. Triangles = squares + 1.5% annual increase in chlorofluorocarbons (CFCs). Circles = squares + 3% CFCs. [Ramanathan et al., 1985]

"For the first time, mankind is making changes on the same scale as natural changes, and the dynamic equilibrium is in jeopardy."

latitude to every 5 or 6 days for an equatorial site. Multiple views at different angles will make it possible to study albedo variations, which contain information on the health and distribution of vegetation, and the grain size and reflectivity of snow and ice fields. HIRIS will be able to identify over 1,000 minerals that have unique spectral signatures in the visible and near-infrared, including iron and magnesium compounds, carbonates, and sulfates. HIRIS will also be able to examine suspended sediments and phytoplankton in coastal and inland waters. In both applications, HIRIS's 192 spectral bands will allow discrimination between organic and inorganic matter, as well as providing the sensitivity to subtle spectral differences needed to distinguish between algal pigments or closely related minerals. (Even changing the bandwidth from 10 to 20 nm would lose much of this information.) HIRIS will also be able to study biochemical processes in vegetation by mapping environmental stresses that manifest themselves as subtle shifts in chlorophyll's absorption spectrum. Furthermore, nitrogen in leaves and lignin (related to cellulose) in stems and branches have detectable spectral signals, although they are not as well-defined as those for minerals. If the signals could be identified, however, it would refine estimates of the carbon and nitrogen balances in living and decomposing vegetation. None of the above functions can be done adequately with existing satellites.

All of this data would be useless unless some way existed to get it to earth intelligibly. Tremendous strides in signal-processing technology have made it possible to send HIRIS's 192 images per view back to earth in almost real-time, at a rate of 300 million bits of information per second. But even after it reached the earth, most of the data would never have been looked at without comparable improvements in data visualization, a computerized function that combines image processing with sequence information. Concurrent- and parallel-processing systems developed at Caltech and JPL have made it possible to compress months' or years' worth of information from multiple sources into false-color "movies." Says Chahine, "How else can you look at, say, 10^{11} bits of information in six minutes? Now we can just archive all this data as it comes in, and the people who need specific parts of the data can take what they want. But when we're looking for trends or anomalies, we don't want to look at it all piece by piece. So we make a movie in the computer, and as we watch the movie, what we are looking for becomes very apparent. Then we can go back to that particular dataset and analyze it in greater detail.

"The earth's climate has always been changing. But the natural variations have always been over a limited range. One reason life was able to develop was that a steady-state climate existed for a long time. The oceans and the atmosphere have been in dynamic equilibrium for billions of years. But now we are drastically disturbing that equilibrium. For the first time, mankind is making changes on the same scale as natural changes, and the dynamic equilibrium is in jeopardy. Venus and Mars started much like Earth, but they never achieved a steady state in the habitable range. Venus got hotter from a runaway greenhouse effect, and Mars got colder as all its CO_2 got tied up as carbonates in rocks. And now look at them—they're dead planets. As we begin celebrating the 500th year of Columbus's discovery, one of our objectives is to work toward celebrating a second 500 years on a planet we can still enjoy."□—*DS*