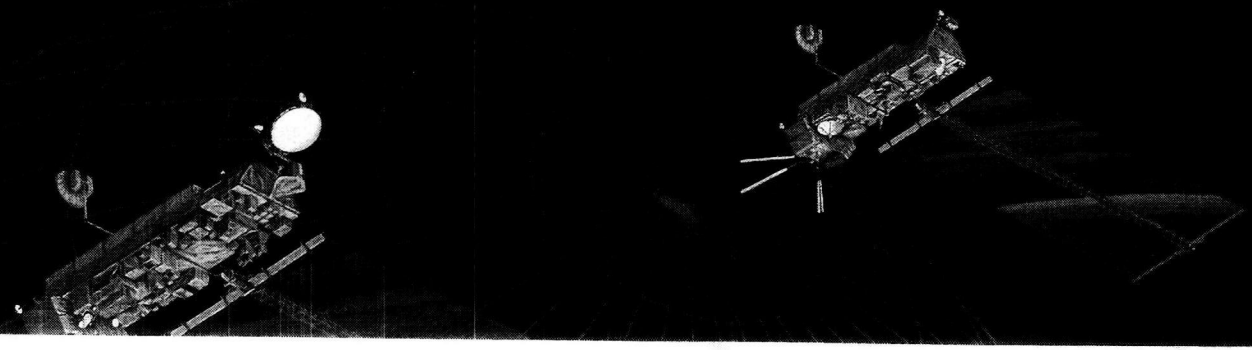
THE EARTH OBSERVING SYSTEM

EOS

A Mission To Planet Earth



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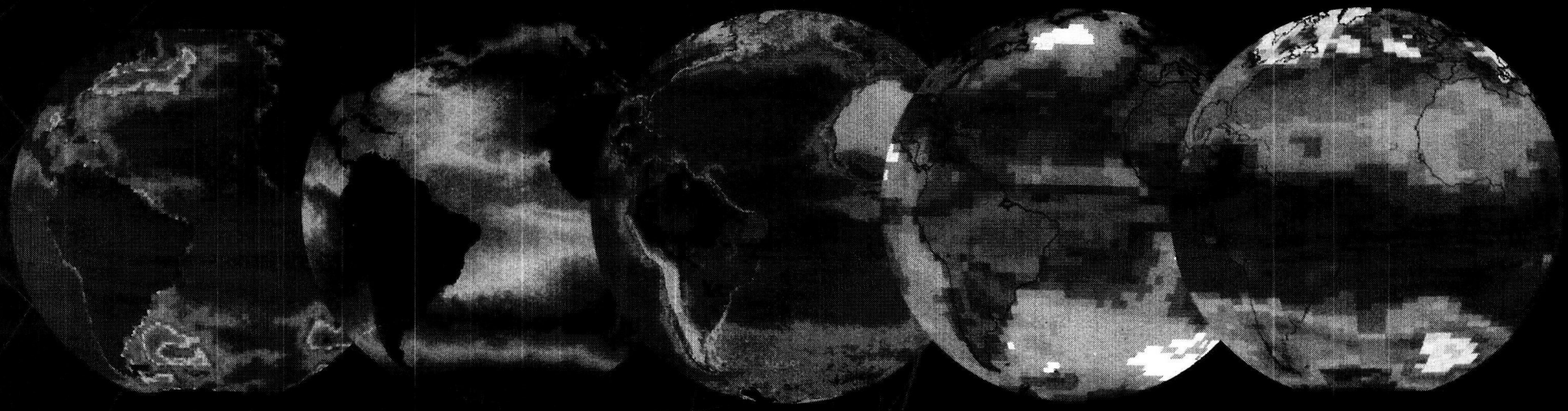

Funding for the U.S. Global Change Research Program will increase by nearly 60 percent, to over $1 billion [in FY 1991]. That commitment, by far the largest ever made by any nation, reflects our determination to improve our understanding of the science of climate change.... Our program allows NASA and her sister agencies and all our international partners to move forward with the "Mission to Planet Earth". That will initiate the U.S. Earth Observing System.

President George Bush
February 5, 1990

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EOS: The Earth Observing System

To understand global change and the increasing demands of human activity, it is essential that we document and comprehend how the Earth works as a system. The international scientific community is organizing research efforts to advance our knowledge of both natural and human-induced global change. The U.S. Global Change Research Program, a consensus interagency plan, defines the U.S. element of those efforts.

Mission to Planet Earth, the central NASA contribution to the U.S. Global Change Research Program, includes two proposed initiatives in the FY 1991 Federal budget: the Earth Observing System (EOS) and Earth Probes.

EOS consists of a space-based observing system, a Data and Information System (EOSDIS), and a scientific research program. It represents the initiation of a comprehensive, global observing system with broad and high-resolution spectral and spatial, as well as long-term temporal, coverage of the Earth. The space component will consist of two series of polar-orbiting platforms, with launch of the first platform in FY 1998. EOS will be supplemented by companion European and Japanese platforms, as well as the continuing operational environmental satellites.

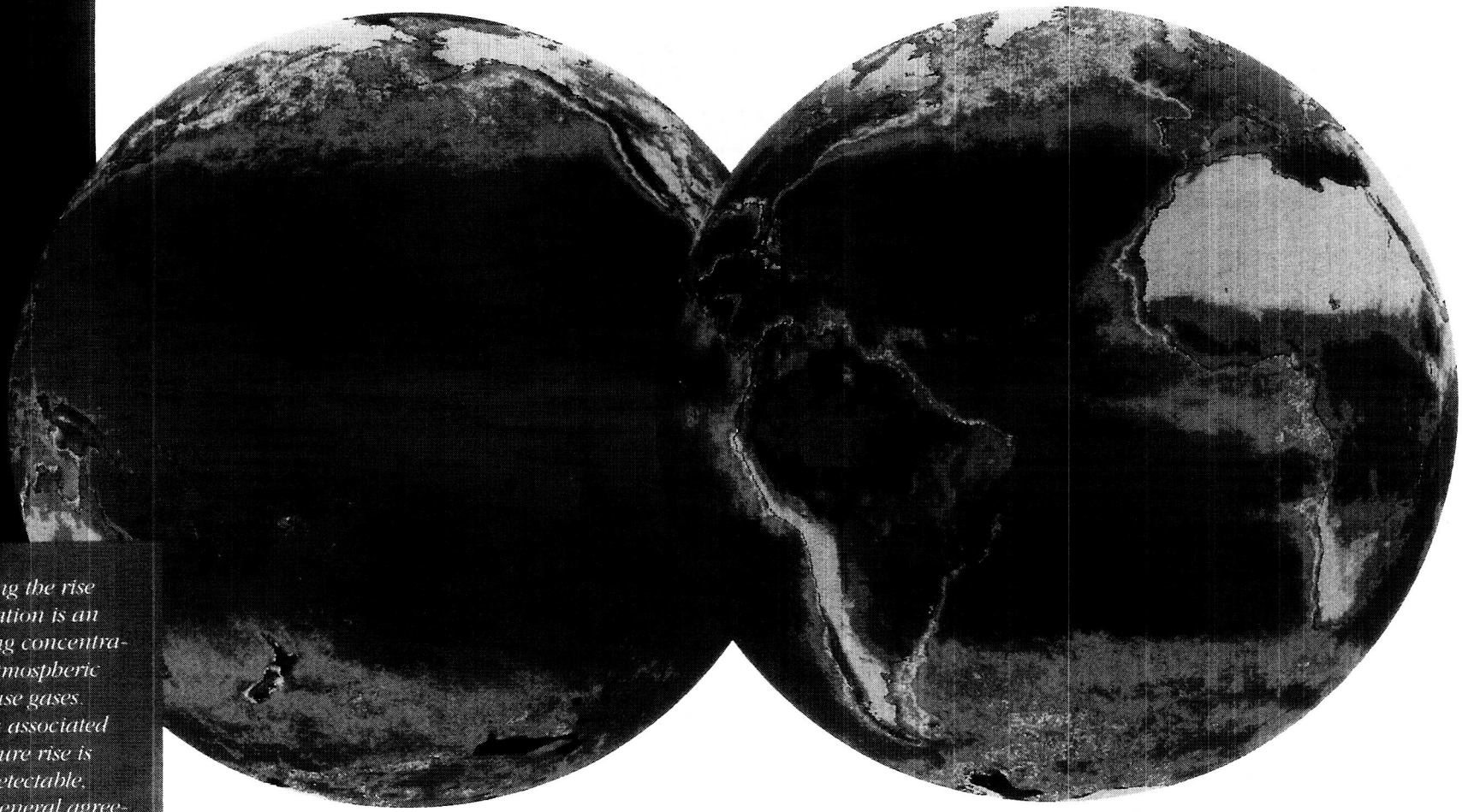
EOS will continue and integrate the measurements now being taken by short-term research missions. It will provide the first coordinated simultaneous measurements of the interactions of the atmosphere, oceans, solid earth, and hydrologic and biogeochemical cycles.

Earth Probes will provide a focus on observing specific Earth processes where smaller platforms and/or different orbits from EOS are required. In addition to complementing EOS, Earth Probes will provide critical near-term observations.

Development of EOSDIS will begin immediately to support the research and analysis of both existing data and those to come from the near-term missions. EOSDIS will be a state-of-the-art information system to foster rapid and easy access for users.

This document presents EOS, Earth Probes, and related precursor research missions—all in the context of supporting the U.S. Global Change Research Program. For additional information, Pre-EOS and EOS Reference Handbooks are available which provide in-depth information on candidate instruments, their measurements, and the Data and Information System.

On the cover: the EOS-A (left) and -B (right) polar platforms. The five discs show (left to right): variable sea-surface topography, sea-surface temperature, a composite of ocean chlorophyll concentration and terrestrial vegetation index, mean cloud cover, and stratospheric ozone.



Paralleling the rise in population is an increasing concentration of atmospheric greenhouse gases. While an associated temperature rise is not yet detectable, there is general agreement that it will occur; the open question regards its rate and magnitude.

Understanding The Earth As A System

We live on a planet of extraordinary complexity; the presence of an atmosphere and oceans with the right chemical composition on a solid planet has supported the development of an abundant diversity of life. Throughout geologic history, the atmosphere, oceans, and land have interacted to produce global environmental change to which life has contributed and adapted. Today, one species of life, humankind, through increasing population and quest for improved quality of life, has developed the capability of changing our global environment in ways that we are only beginning to perceive, but do not fully understand.

In some cases, such as the depletion of the Earth's energy and mineral resources, the effects of human activity are obvious. In other cases, such as the alteration of atmospheric chemical composition, the processes of change are difficult to document, and their consequences harder to foresee. Moreover, the effects of many human-induced changes cannot readily be distinguished from the results of natural change over time periods of decades to centuries.

We now know that we have embarked on a global experiment, but we do not know the consequences. Model predictions suggest that the Earth should be warming in response to increasing carbon dioxide and other gases in the atmosphere, but observations are ambiguous. Is the signal lost in the noise of natural climate variability, or are there other processes at work? Until we more completely understand the Earth system, we will not be able to answer such crucial questions.

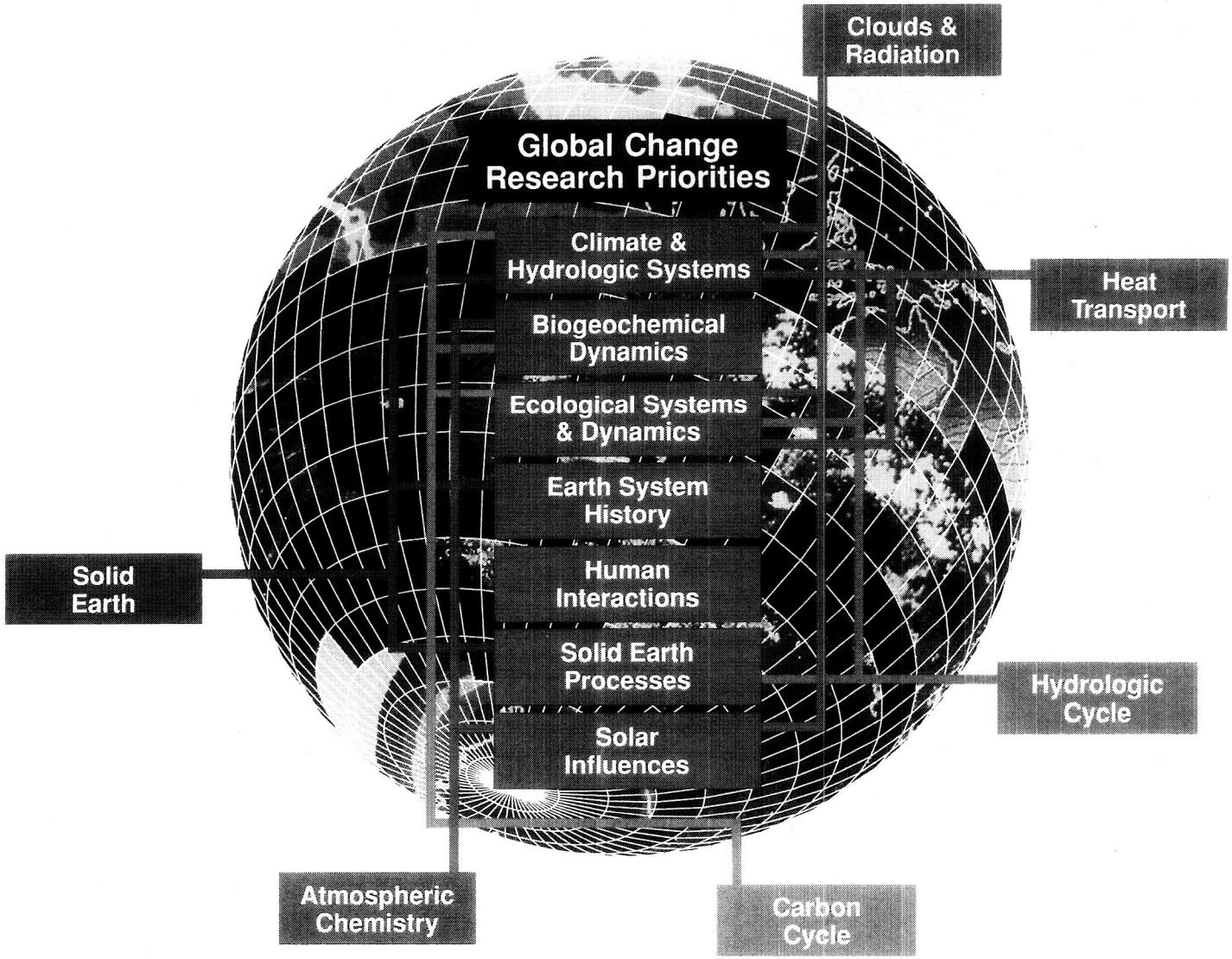
The oceans, atmosphere, and ice-covered regions of the globe are now recognized to be closely coupled in shaping the Earth's weather and climate. Both terrestrial and oceanic biota are recognized as exerting a major influence on global climate and the chemical cycles important to life. But the fundamental questions about how the Earth system works remain unanswered.

Over the past 40 years, our view of the solid Earth has been dramatically transformed. The earlier notion of a placid, static globe has been replaced by the dynamism of plate tectonics. Patterns of mountain-building, volcanism, and earthquake activity all fit consistently into this new view.

It is essential that we understand how components of this system interact—from the short time scales of weather systems to the millennia of geological time—and how we affect these interactions. Until we have that understanding, we will not be able to predict how human activities will change the environment.

A global view of the Earth's biosphere. Shown are three-year composite images of ocean chlorophyll concentration (increasing from purple to red) and land vegetation index (increasing from tan to green), derived from NASA's Nimbus-7 Coastal Zone Color Scanner and the NOAA-7 Advanced Very High Resolution Radiometer, respectively.

Recognizing the potential for global change, the international community is organizing research efforts to understand the Earth system. The Global Change Research Program, resulting from interagency consensus, defines the US contribution to those international efforts.



A Plan For Action

The demonstrated human role in global change requires that we develop a comprehensive program of Earth studies that transcends traditional disciplinary boundaries. Our goal is to obtain a scientific understanding of the Earth as a system, from which we hope to develop a capability to predict future change.

The key to understanding is accurate observations and modelling of the crucial interacting processes. Such observations of the state of the Earth are critical for providing a system for early warnings of change. To obtain that basic information, we need appropriate instruments deployed both on the Earth's surface and in space. Satellite remote sensing provides global and long-term continuous measurements for monitoring the entire planet. Surface-based measurements are required both to validate the space-based observations, to provide more detailed studies, and to observe those processes not accessible from space.

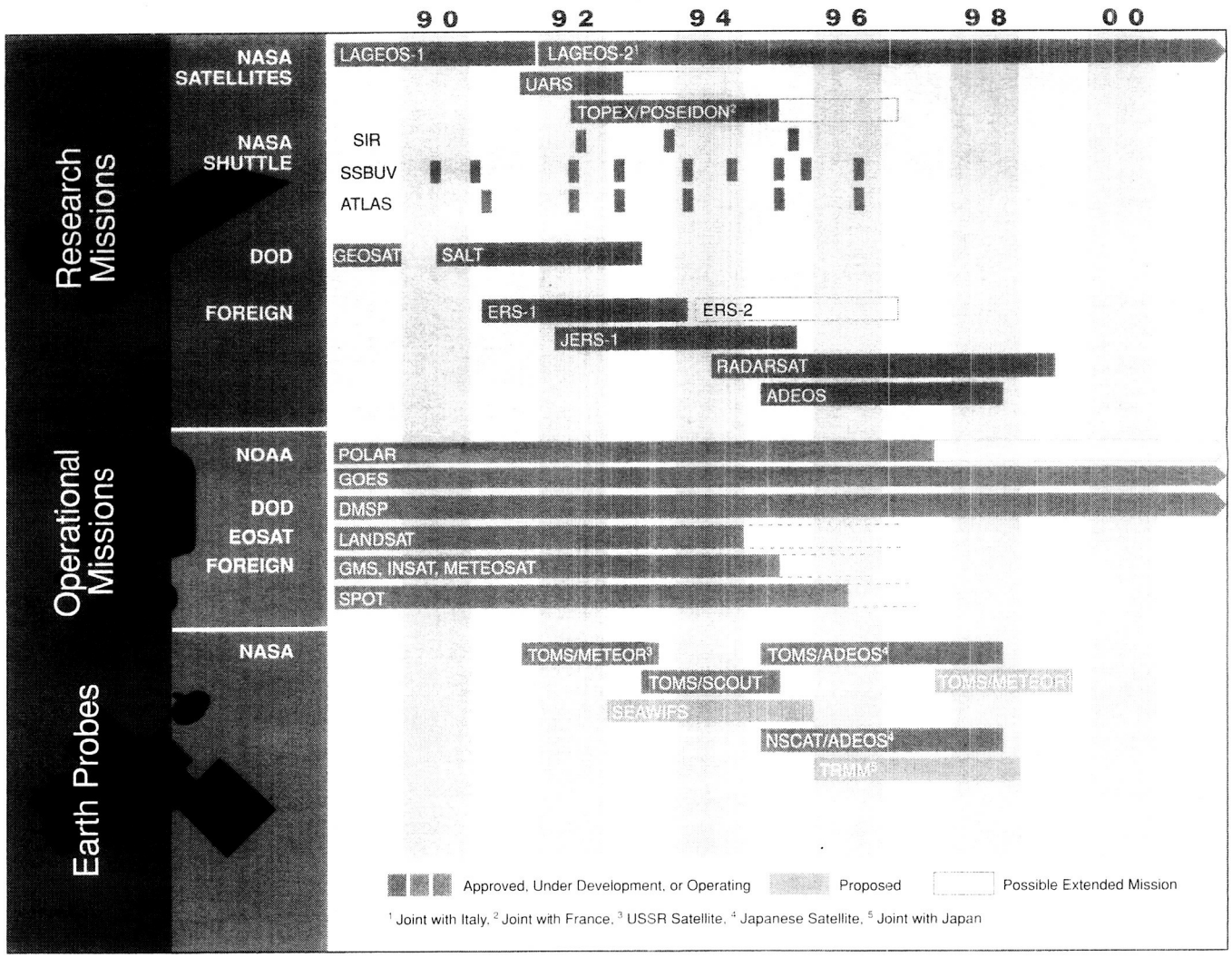
The international scientific community is developing programs to address global change. The World Climate Research Programme, sponsored by the International Council of Scientific Unions (ICSU) and the World Meteorological Organization, focuses on physical aspects of climate systems: the role of clouds and radiation, ocean circulation, air-sea interaction, and the effects of global water and energy budgets on climate. ICSU has established the International Geosphere-Biosphere Programme to describe and understand the interactive chemical and biological processes that regulate the total Earth system.

In response to the scientific challenge and a national perception that the U.S. must take a leadership role in global change research, a federal interagency Committee on Earth Sciences was formed under the President's Science Advisor to develop a plan for action. With remarkable agreement and clear consensus, representatives of thirteen federal agencies have produced the first U.S. Strategy for Global Change Research.

The integrating priorities of this program are to document change in the Earth System using observational programs and data management systems, to carry out focused studies on controlling processes to improve our understanding, and to develop integrated conceptual and predictive models.

For the first half of the 1990s, space-borne contributions to the Global Change Research Program will come from the missions described below. These include the initiation of NASA's Earth Probes as well as the EOS Data and Information System (EOSDIS) which will support study of available satellite data. The launch of the first of NASA's EOS polar platforms is in FY 1998 and will mark the beginning of a comprehensive and long-term measurement system.

Schematic representation showing how interdisciplinary components of NASA's EOS science program relate to the corresponding science priorities of the U.S. Global Change Research Program.



NASA's traditional focus on discipline-specific missions has emphasized the development of improved sensors, placing lower priority on data systems. While the utility of remote sensing has been demonstrated, the full potential of satellites has yet to be realized in Earth science.

Focused Near-Term Observations

Earth remote sensing has evolved from developing and demonstrating technology to focusing on specific research and operational topics. For example, NASA's Seasat and the series of Nimbus satellites have demonstrated the utility of active and passive microwave systems for characterizing the oceans and atmosphere.

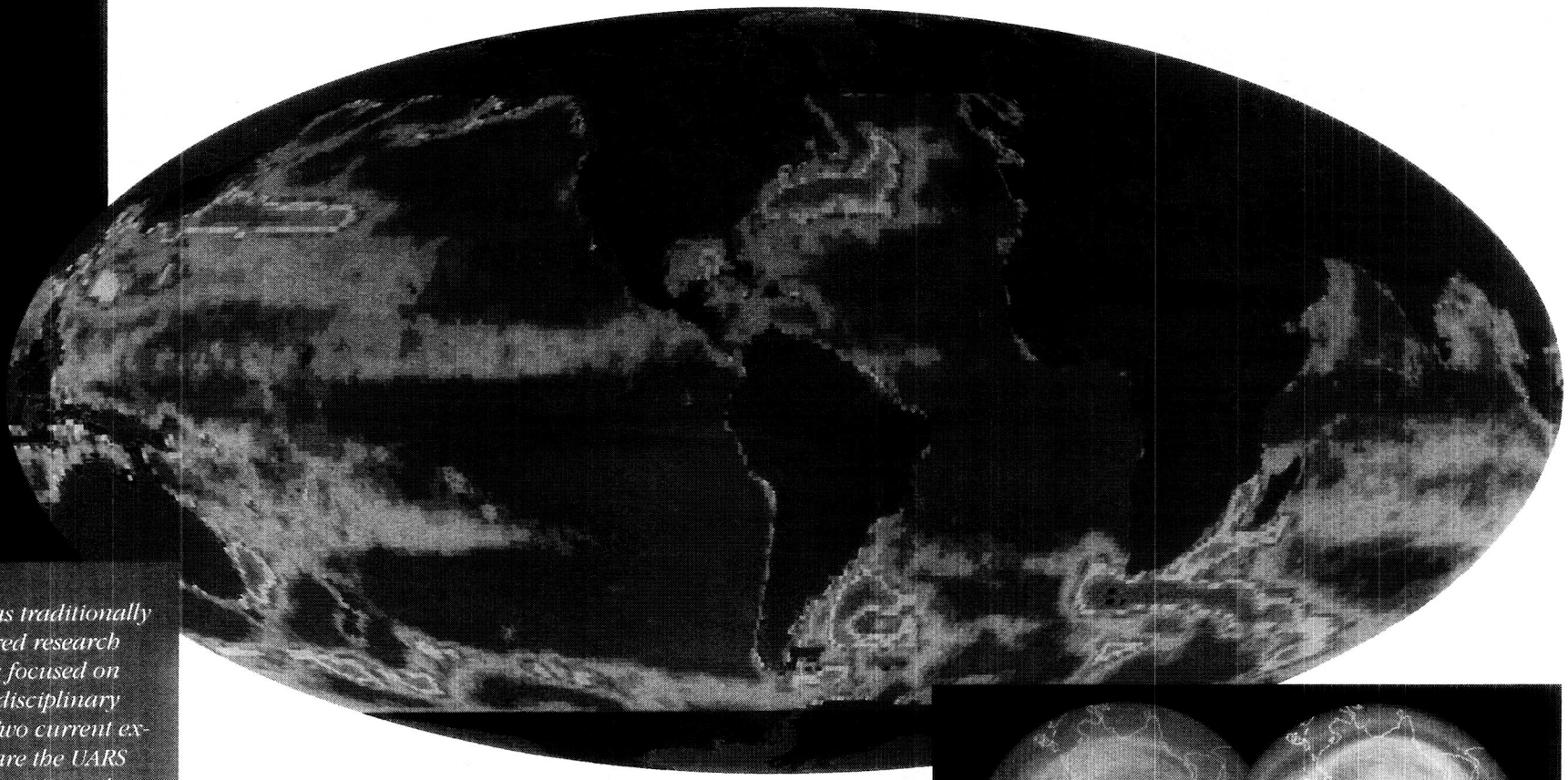
Building on the lessons learned, two research missions under development are the Upper Atmosphere Research Satellite (UARS) and TOPEX/Poseidon, focused on atmospheric chemistry and oceanic circulation, respectively. There are also sensors for short-term deployment from the Space Shuttle: Shuttle Imaging Radar (SIR), Shuttle Solar Backscatter Ultraviolet sensor (SSBUV), and Atmospheric Laboratory for Applications and Science (ATLAS). These address the development and utilization of synthetic aperture radar, accurate measurements of ozone in the upper atmosphere for cross-calibration purposes, and observations of solar influences on atmospheric chemistry. Finally, accurate tracking of the two laser geodynamics satellites (LAGEOS-1, -2) provides gravity and geodetic data.

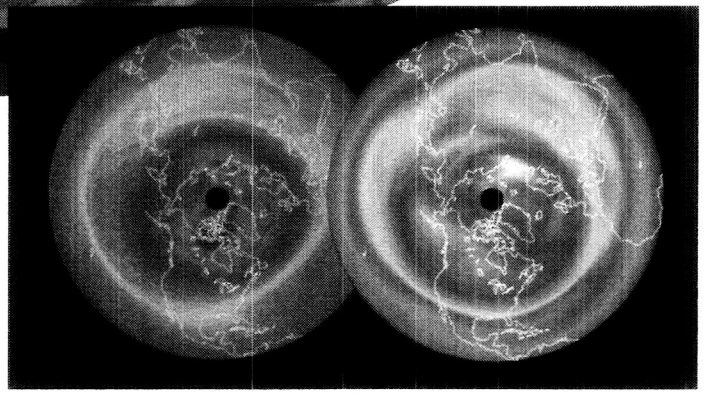
In addition, the U.S. Department of Defense has flown an altimetric satellite, GEOSAT, and plans another, SALT, for observing oceanic circulation. Foreign missions include the European Remote Sensing satellite (ERS-1), for ocean observations; Japanese Earth Resources Satellite (JERS-1), for global mapping of resources; Canadian Radarsat, for sea-ice mapping; and Japanese Advanced Earth Observing Satellite (ADEOS), which will include two of NASA's proposed Earth Probe sensors.

Included in NASA's proposed Earth Probes are sensors destined for flights of opportunity: Total Ozone Mapping Sensor (TOMS) to provide interim ozone observations until the flight of EOS, Sea-viewing Wide-Field Sensor (SeaWiFS) to provide improved observations of oceanic chlorophyll, and Scatterometer (NSCAT) to provide marine surface winds. The Tropical Rainfall Measuring Mission (TRMM) will provide the first spaceborne measurements of low-latitude rainfall.

Throughout the first half of the 1990s, the research missions discussed below will provide remotely sensed data for the Global Change Research Program. They will be complemented by operational missions currently consisting of geosynchronous and polar-orbiting satellites for weather forecasting and land measurements. Simultaneously, the EOS Data and Information System will provide a means for accessing data from these missions and integrating them in global change studies—all in preparation for the comprehensive Earth Observing System of the second half of the 1990s.

This table shows the distribution of Earth-related missions in the pre-EOS era. Included are those proposed Earth Probes which have been defined.





NASA has traditionally configured research missions focused on specific disciplinary topics. Two current examples are the UARS and TOPEX/Poseidon missions, addressing stratospheric chemistry and ocean circulation, respectively.

Oceanic Circulation, Atmospheric Chemistry

Two major missions, each addressing a specific question relating to global change, are under development for launch in the early 1990s. TOPEX/Poseidon is focused on oceanic circulation and the Upper Atmosphere Research Satellite (UARS) on atmospheric chemistry.

TOPEX/Poseidon. The large-scale movement of water in the ocean affects climate by transporting heat from the equator to the poles. This oceanic circulation is one of the weak links in our understanding of the physical climate system. Surface and deep currents, upwelling, and bottom-water formation are involved. But to observe this complex system has proved extraordinarily difficult with conventional means. To achieve a global synoptic view of the circulation will require satellite measurements as well as *in situ* studies. NASA and France's Centre National D'Etudes Spatiales have designed a joint mission, TOPEX/Poseidon, that will use a radar altimeter system deployed in an orbit specifically designed for precise measurements of broad-scale ocean surface currents unobtainable via shipboard observations. It will be launched in 1992 on an Ariane rocket.

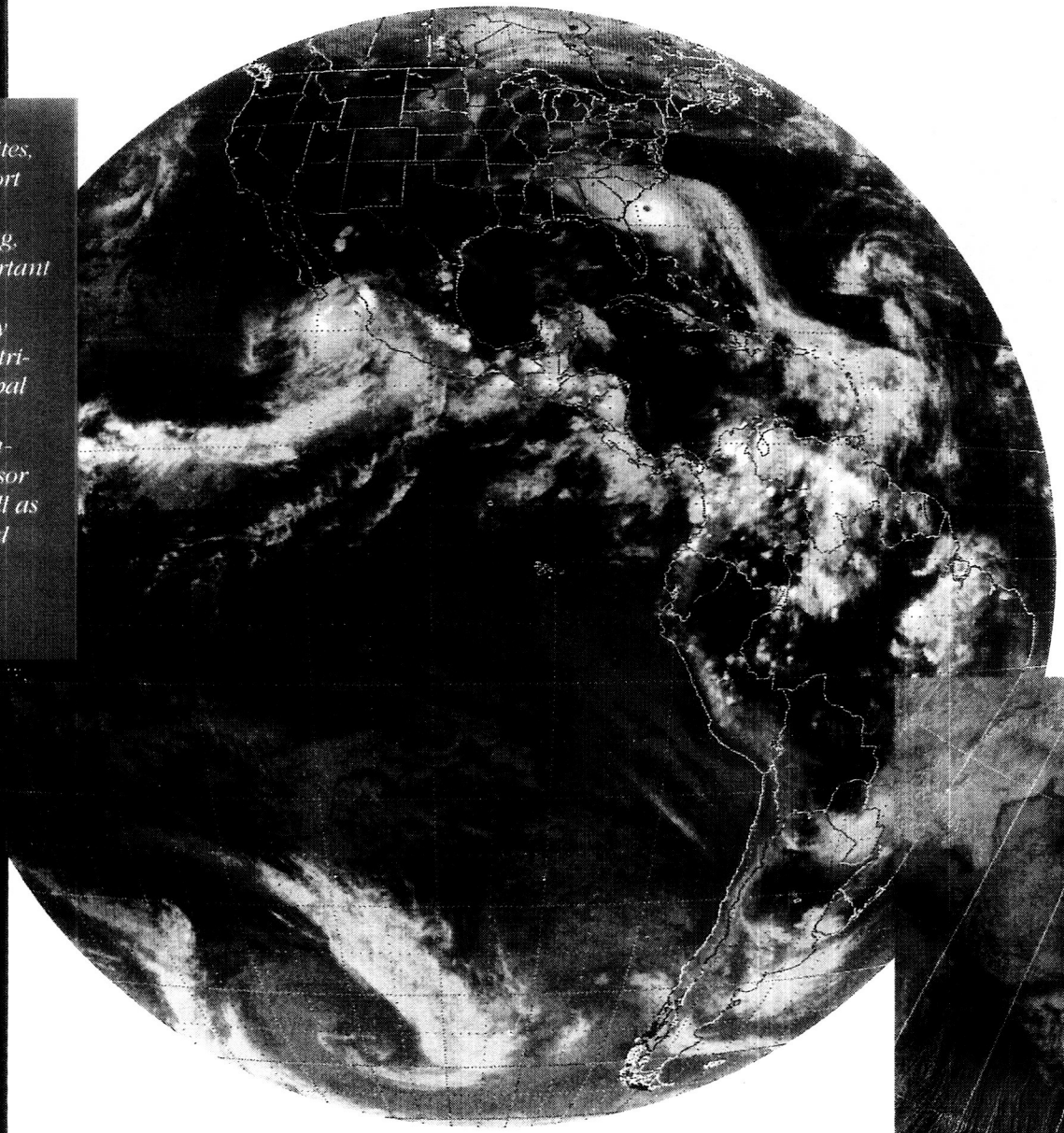
TOPEX/Poseidon will give accurate measurements of currents and tides, but with only a single altimeter, it cannot resolve the smaller-scale ocean eddies which are also important in ocean heat transport and biological processes. With at least two altimeters flying on different satellites in the EOS era, the broad spectrum of oceanic circulation can be monitored.

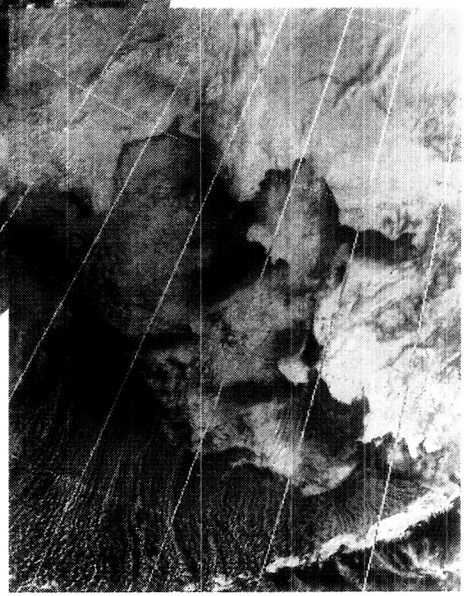
UARS. Major questions of atmospheric chemistry remain unanswered despite having received much attention in recent years: What causes ozone variations? How are the chemical, radiative, and dynamic processes of the stratosphere coupled? UARS, planned for launch in 1991, will gather data related to the chemistry, dynamics, and energetics of the ozone layer. UARS data will be used to study energy input, stratospheric photochemistry, and upper atmospheric circulation. UARS will help us understand and predict how the nitrogen and chlorine cycles—and the nitrous oxides and halocarbons which maintain them—relate to ozone balance. It will also observe diurnal variations in short-lived stratospheric chemical species important to ozone destruction.

UARS, primarily focused on the upper atmosphere, will only provide a very limited set of companion measurements in the troposphere. Moreover, UARS, like most research missions, has a relatively short (two to five years) lifetime. EOS will provide continuing measurements, as well as more complete coverage of chemical species in both the stratosphere and troposphere.

Sea-level variability measured by the U.S. Navy's GEOSAT over a two-year period revealing fluctuations in the western boundary currents and Antarctic Circumpolar Current (increasing to red-yellow). The smaller images show two atmospheric constituents that were measured by the LIMS sensor aboard Nimbus-7 during the winter of 1979: left, nitrogen dioxide; right, nitric acid (increasing from blue to red).

Operational satellites, developed to support activities such as weather forecasting, represent an important source of global observations. They can make key contributions to the Global Change Research Program, given improvements in sensor calibration, as well as the generation and archival of data products.





Research Use Of Operational Data

Initial pictures of weather from space were produced from a U.S. TIROS satellite in 1960. Today, the polar-orbiting and geostationary environmental satellites of the National Oceanic and Atmospheric Administration, the Defense Meteorological Satellite Program (DMSP), the commercial venture Eosat, and their counterparts around the world provide valuable, real-time information about the changes in the world's weather and land surface. In addition, the operational satellites yield information on climate variables, including surface temperatures, wind velocities, land cover and usage patterns, snow cover and sea ice, cloudiness, global precipitation, and the Earth's radiation budget. This operational system works well: the real-time data provide continual warning of short-term weather hazards such as hurricanes, storms, and other extreme events.

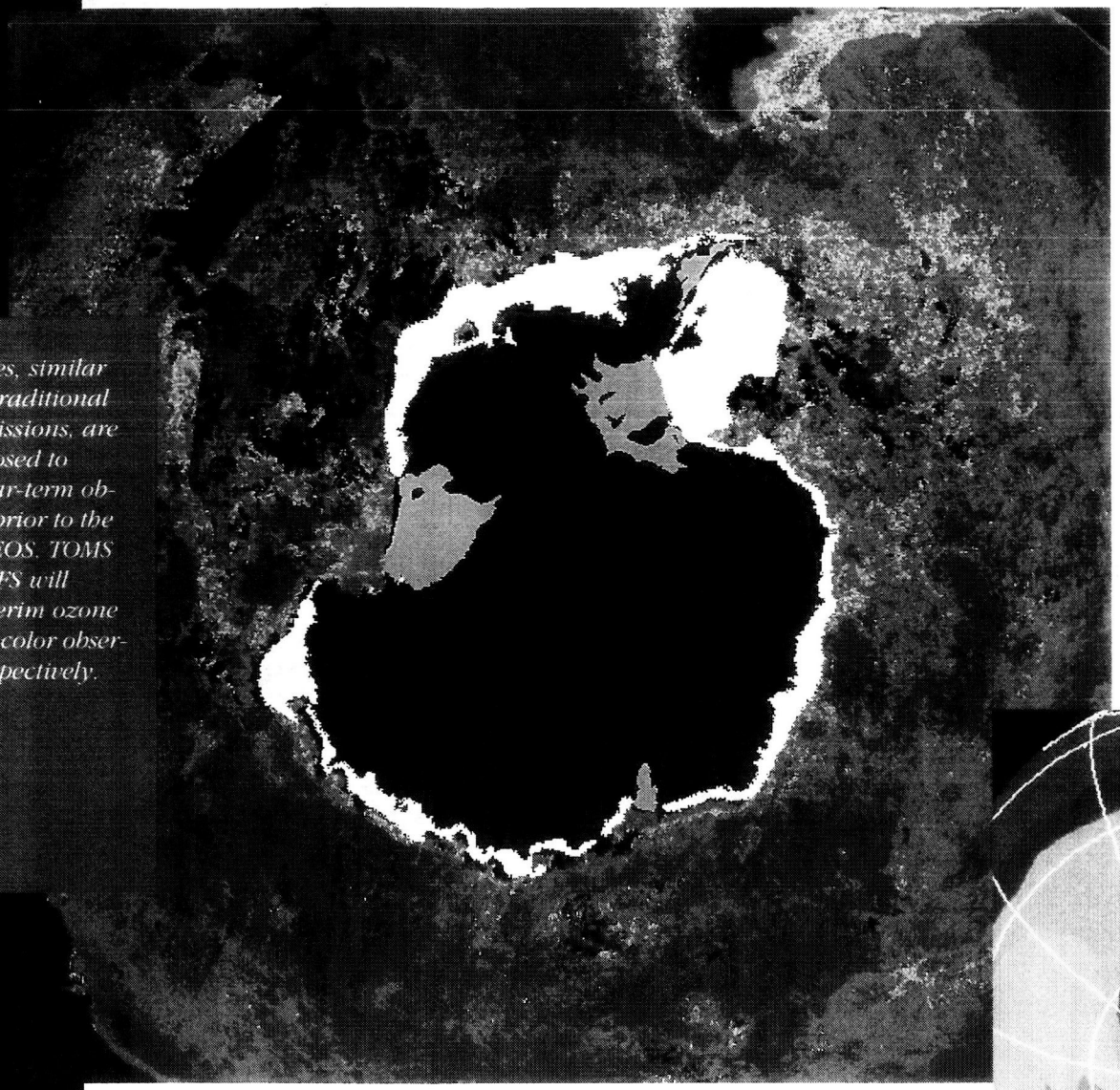
These data have provided a tantalizing first view of the workings of the components of the Earth system. Moreover, the data collected by the operational systems have the potential for providing useful information on global change. They constitute a record, now over a decade long, of baseline information against which global change can be measured. In addition, new data products are being developed to exploit the data for use in longer-term climate studies.

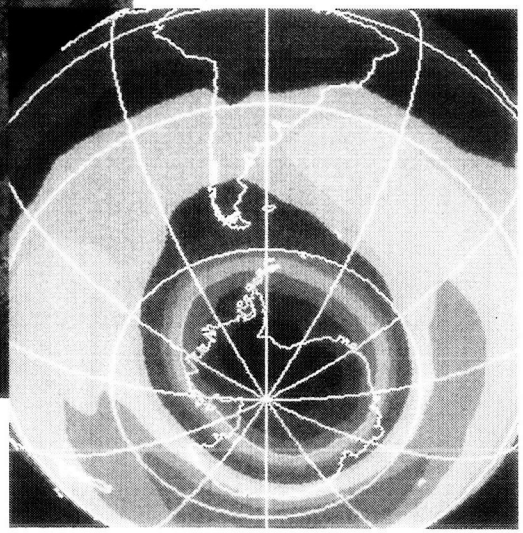
At the same time, since the systems are driven by operational and commercial requirements, the full use of the data for research on global change has been limited. The spectral coverage of the environmental and Landsat systems is limited, the repeat coverage of Landsat is infrequent and the commercial viability and hence continuity of Landsat is in doubt. It has not been easy for researchers to access data, either for reasons of cost or because data do not exist or are not available in formats that can be easily used.

The next logical step for these systems is to address long-term calibration and validation issues, generate research quality products, and make these products available to a wide variety of users in a manner compatible with the EOS Data and Information System. In this way, the research community will have a means to work with large data sets as it prepares for the new research missions and EOS itself.

It is essential that the operational satellite observations extend into the future in order that the baseline information continue. With the generation of research quality products and easy access to archives, the operational systems can significantly complement the research missions, Earth Probes, and EOS to provide the comprehensive data set necessary to document and understand global change.

The larger image from NOAA's GOES shows cloud patterns on September 22, 1989; note Hurricane Hugo off the coast of South Carolina. The smaller visible image from DOD's DMSP shows prominent sea-ice features and wind rows in the Bering Sea on March 2, 1988.





Earth Probes, similar to smaller traditional research missions, are being proposed to provide near-term observations prior to the launch of EOS. TOMS and SeaWiFS will provide interim ozone and ocean color observations, respectively.

The Ozone Hole, Ocean Productivity

Earth Probes are being proposed to obtain near-term observations of specific Earth processes prior to EOS, as well as to complement EOS in those cases where smaller platforms and/or orbits other than EOS are required. Earth Probes are scheduled to begin flying in 1991 with a satellite launch every two to three years.

TOMS. The Total Ozone Mapping Spectrometer (TOMS), the first Earth Probe, will measure atmospheric ozone. The habitability of the Earth depends on maintaining the ozone layer, which absorbs harmful ultraviolet light. We now know that ozone depletion is caused by complex, coupled chemical reactions. In the early 1970s, a warning was sounded that the chlorofluorocarbons used in widespread applications could cause depletion of the ozone layer. The TOMS sensor on Nimbus-7 has provided a continuous global record of ozone over the full depth of the atmosphere since 1978, but the instrument is now reaching the end of its useful life. To continue these measurements, NASA has made arrangements for a TOMS instrument to fly on a Soviet Meteor-3 Satellite and on the Japanese Advanced Earth Observation satellite; a low-cost U.S. satellite to carry a TOMS payload is also being designed. Thereafter, instruments to monitor ozone will be carried on future NOAA satellites.

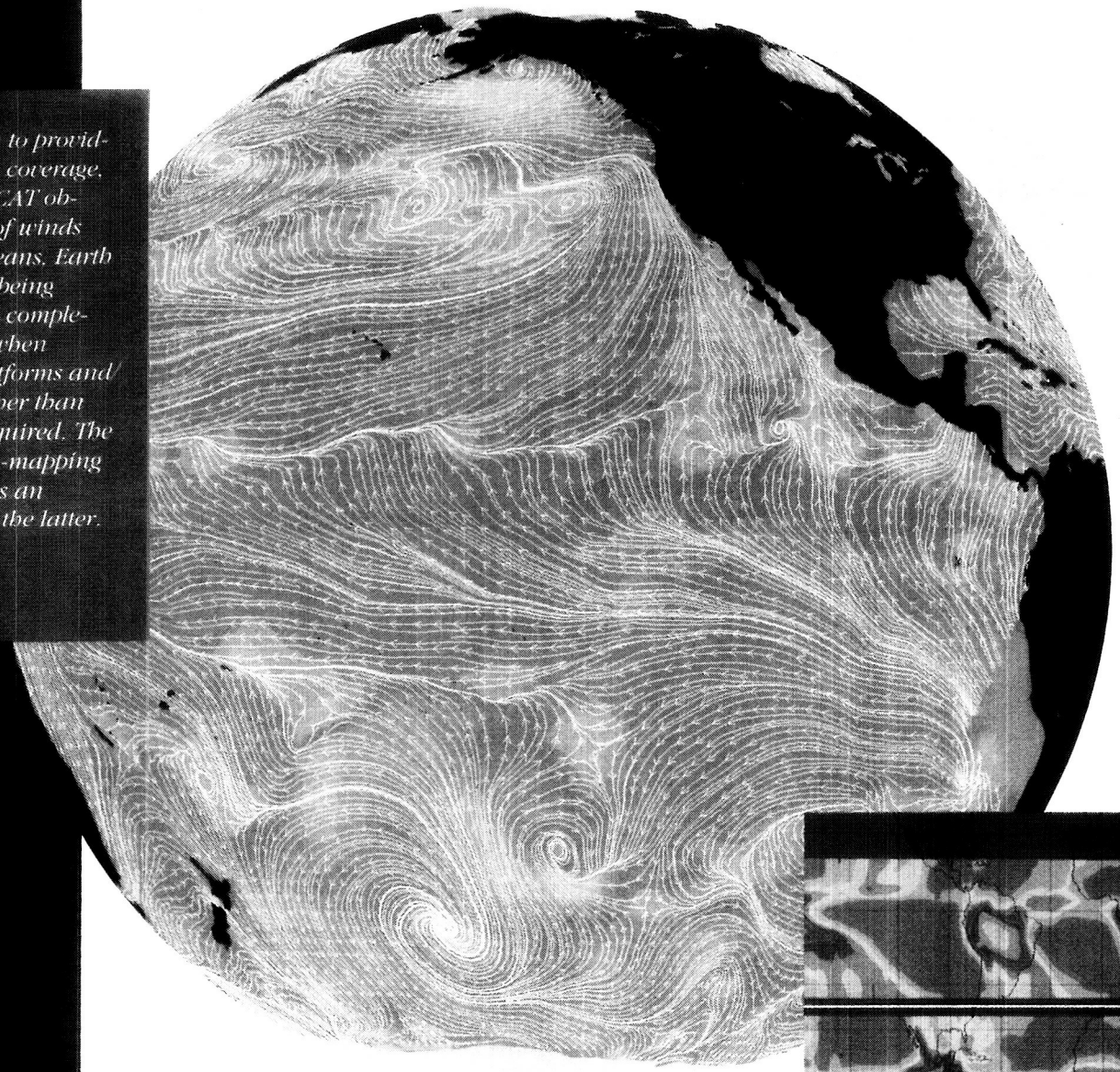
SeaWiFS. One of the next Earth Probes is the Sea-viewing Wide-Field Sensor (SeaWiFS), an ocean color scanner. Biological processes in the ocean are critical to biogeochemical cycles. In the upper ocean, primary production by phytoplankton is a key parameter in regulating carbon flux in the sea. Thus, it is essential to understand its magnitude and variability. However, present uncertainties in estimates of oceanic primary production are larger than the annual rate of atmospheric carbon dioxide increase.

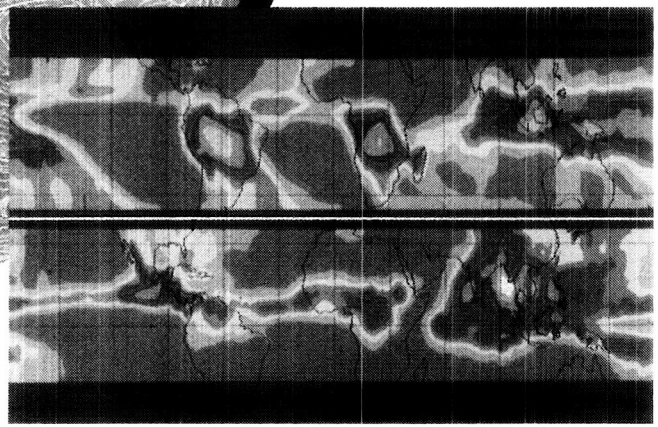
To address this need, NASA has defined performance specifications for the SeaWiFS sensor which will measure ocean color related to phytoplankton chlorophyll. SeaWiFS will be able to measure chlorophyll in the open ocean where the signal is low, distinguish between phytoplankton pigments and sediment in coastal water, and make the necessary atmospheric corrections. These data will provide the first estimates of the mean and variable rates of primary production in the world oceans.

Instruments planned for EOS will continue previous ocean color time series. In addition, with their higher spectral resolution, they will have important new capabilities that will accurately resolve photosynthetic potential and plankton types, thus increasing our capability to study the interactions of marine ecosystems and global change.

Ozone concentration (smaller image) from TOMS showing the ozone hole for October 1989 (increasing from purple-blue to yellow-red). Four-year composite of chlorophyll concentration (larger) from CZCS (increasing from purple-green to yellow-red); also shown is the typical minimal extent of sea ice in summer (white).

In addition to providing interim coverage, such as NSCAT observations of winds over the oceans, Earth Probes are being proposed to complement EOS when smaller platforms and/or orbits other than EOS are required. The TRMM rain-mapping capability is an example of the latter.





Marine Winds, Tropical Rain

In the tropical Pacific Ocean, the changing winds, rainfall, and heat from the ocean are the signals and drivers of El Niño, the periodic climate anomaly that has global implications. Accordingly, NASA is developing systems to measure marine surface winds and rain as part of its Earth Probes program.

NSCAT. Winds drive ocean currents and modulate the fluxes of heat, moisture, gases, and particulates between the air and the sea. Thus, knowledge of ocean surface winds is crucial for understanding the ocean-atmosphere coupling. A better understanding of the marine boundary layer and troposphere will also improve numerical weather predictions.

At present, most wind observations over the oceans come from ships, and the data are often inaccurate and geographically sparse. The NASA Scatterometer (NSCAT), an active radar system in a sun-synchronous orbit, can measure both wind speed and direction over at least 90 percent of the ice-free global oceans every two days. NSCAT is now being developed for space flight on the Japanese ADEOS satellite with launch in 1995. This flight schedule will allow an overlap with the extended mission of TOPEX/Poseidon, thus providing an estimate of the wind forcing and ocean current response.

The absence of a co-located microwave radiometer on ADEOS precludes correction of NSCAT data for contamination by atmospheric water or the identification of rain-induced errors, thus leading to subtle inaccuracies and geographical biases. EOS instrumentation will remedy these deficiencies, as well as continue the measurement series begun by NSCAT.

TRMM. The Tropical Rainfall Measuring Mission (TRMM), a joint effort between the U.S. and Japan, is being proposed to test the feasibility of using active and passive microwave data, together with visible and infrared, to derive rainfall amount and distribution between 35 degrees north and south latitude. In addition, some information about the vertical distribution of rain in thunderstorms will be obtained. TRMM seeks at least a three-year data set of monthly averaged rainfall. As part of EOS, an additional TRMM package is proposed for the Space Station in order to provide a decade of continuous observations.

TRMM data will be used directly in climate models that are critical to understanding global change. However, TRMM will not measure precipitation outside the tropics and subtropics, and it will have relatively large sampling errors over land. These problems will be partially alleviated by using the TRMM package on Space Station in conjunction with complementary sensors on the EOS polar platforms.

The larger image shows surface streamlines (white lines with arrows) and wind speeds (increasing from blue-purple to red-yellow) from the Seasat Scatterometer on September 14, 1978. The smaller shows 1988 Northern Hemisphere winter (top) and summer (bottom) estimates of total rainfall based on infrared observations from the geostationary weather satellites (increasing from red-yellow, through green-dark blue, to light-blue).

Integrated, Long-term Observations

Understanding global environmental change requires knowledge of the entire Earth system. A new concept, Earth System Science, has developed to describe how its components and their interactions have evolved, how they function, and how they may be expected to continue to evolve.

The ultimate goal of Earth System Science is to develop the capability to predict environmental changes, both natural and human-induced, that will occur in the future. Meeting this challenge for the next decade to century requires the integration of knowledge from the traditional disciplines and information from many different sources into a coherent view of the Earth system.

Earth remote sensing has matured as a result of technology development and utility demonstrations. But even as this has occurred, Earth science has continued to be organized along traditional disciplinary lines. With the understanding and experience which has grown within these disciplines, with new technology, and with the challenge of understanding Earth as a system, we are now ready to pursue Earth System Science.

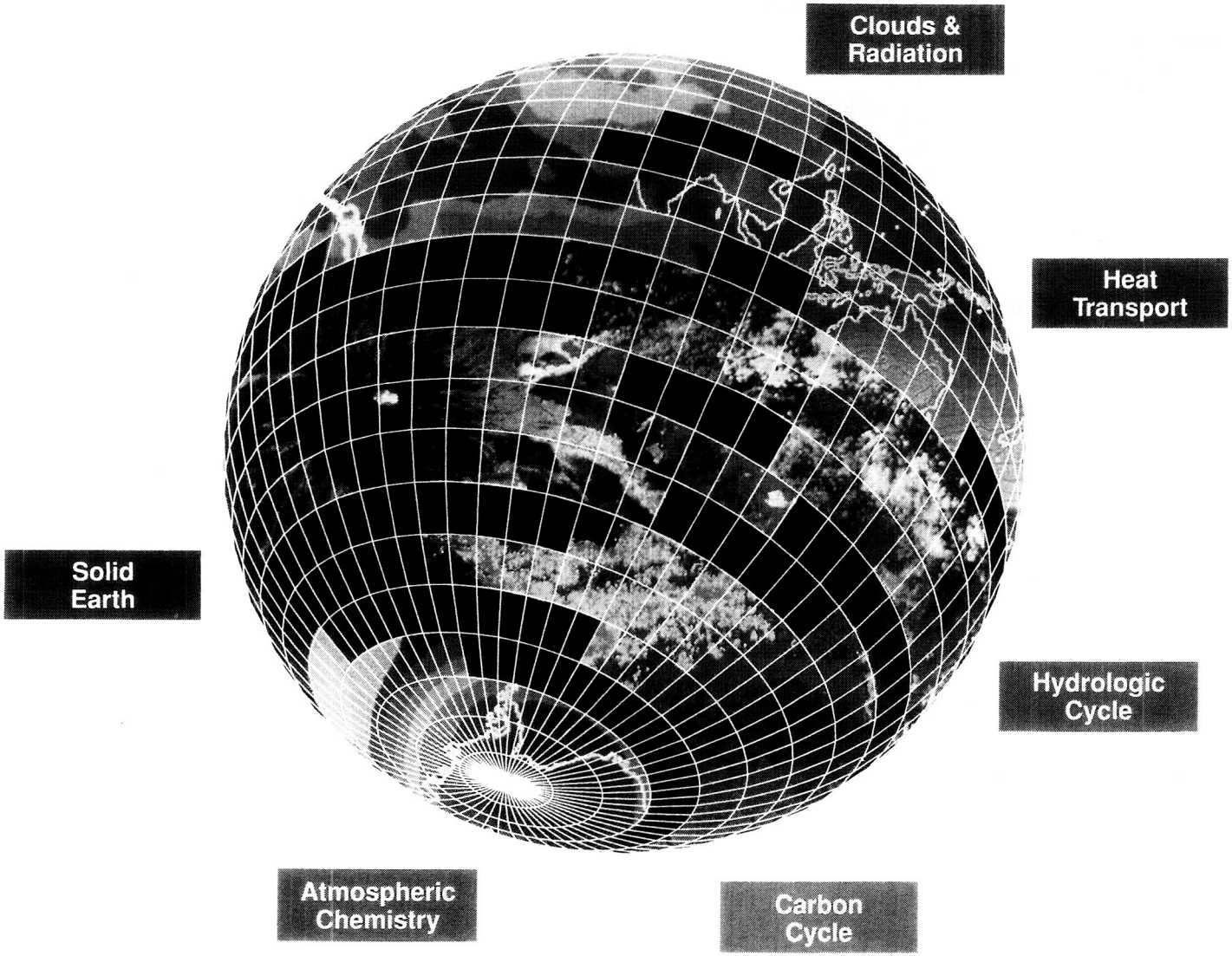
We can now shift our focus from traditional disciplines toward interdisciplinary components of the Earth system as discussed in the following pages: the influence of clouds and radiation balance, role of oceans and atmosphere in heat transport, hydrologic and carbon cycles, changing composition of the atmosphere, and geological and geophysical processes.

EOS has been designed to meet observational needs of Earth System Science. It will operate for 15 years, a time period which encompasses a large span of major environmental change, ranging from several atmospheric biennial oscillations, three to five El Niños, and an entire solar cycle. It will provide a sufficiently large platform to accommodate appropriate suites of sensors so that multiple views of the same location on Earth at the same time will avoid atmospheric-induced uncertainties. It will provide broad and high-resolution spectral and spatial coverage. It will feature a fixed payload for the duration, so that it can provide a consistent set of observations.

One particular strength of EOS is that it will provide, for the first time, a long-term, simultaneous set of observations of the same phenomena on ever-increasing spatial scales (local, regional, global) that can be used to integrate and extrapolate our understanding of ecological and hydrological processes.

The EOS Data and Information System (EOSDIS) will not only provide access to EOS and appropriate complementary ground-based data, but will also support the research and analysis of data which exist today and which will come from pre-EOS missions.

Schematic representation of interdisciplinary components of NASA's EOS science program.



Given the maturity of remote sensing and advances in computer technology, the traditional approach can now give way to one more appropriate to understanding the Earth as a system. The potential now exists to specify — and collect — integrated, long-term, consistent Earth science data sets.

What Is The Influence Of Clouds?

The energy balance of the Earth's climate system is determined by the balance between absorbed and emitted radiation. For the Earth as a whole, and over long time periods, there is a near balance of net radiation at the top of the atmosphere. On shorter time scales, the variable distribution of heating and cooling provides the sources and sinks of energy which drive the circulation of the atmosphere and oceans.

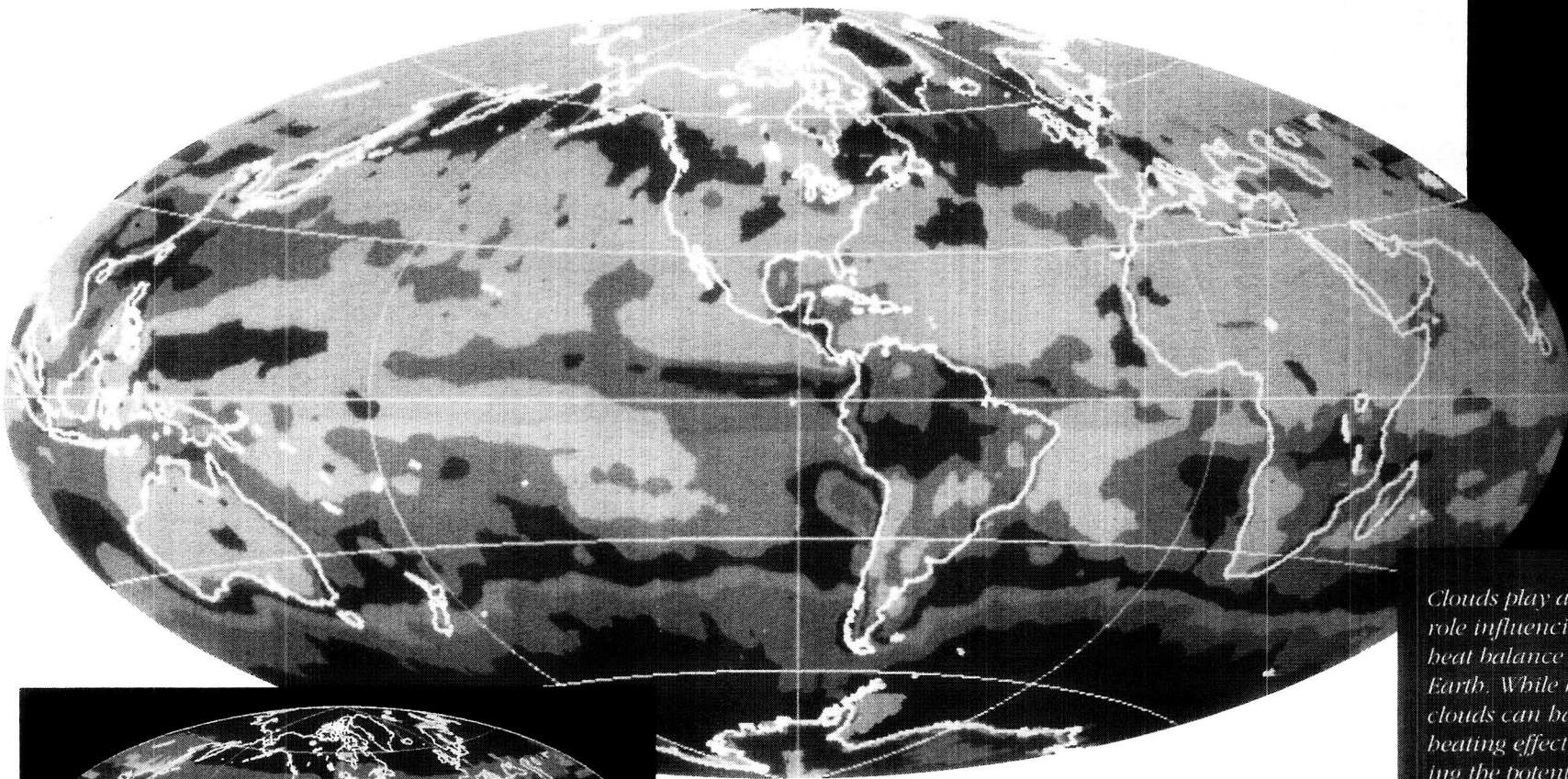
Throughout the atmosphere, radiative heating and cooling compete with other processes such as evaporative cooling or latent heat release to determine the temperature. Radiation is also important in partitioning energy between the atmosphere and the continental surface and between the atmosphere and the oceans, thereby determining the extent to which the oceans moderate climate change. Over land, the solar flux received at the surface has a strong influence on the hydrologic cycle and the biosphere. To understand all of these processes we must monitor the parameters that govern the radiation balance.

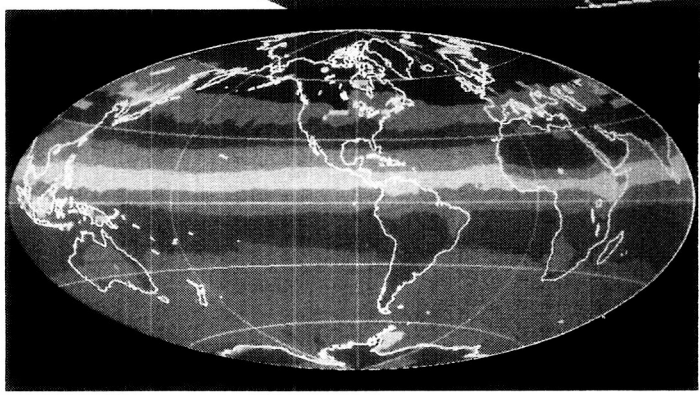
The incoming solar radiation heats the atmosphere and the Earth's surface. The Earth and atmosphere cool by re-radiating a portion of the energy at much longer wavelengths. The difference in radiation at the top of the atmosphere and at the surface is the net radiative heating or cooling of the atmosphere. This difference can be monitored best from space.

The principal attributes of the atmosphere that affect the radiative fluxes must also be monitored to determine the processes that cause changes in the radiative balance. Such measurements have been made from space through the use of operational satellites and the Earth Radiation Budget Experiment. The results from these studies, only recently available, tend to confirm that low level clouds cause cooling through reflection of solar radiation whereas high level clouds cause heating through absorption and reflection of surface radiation. Further long-term measurements will be required to establish the validity of these initial conclusions.

EOS instruments will provide improved spatial resolution and high spectral resolution observations of clouds and more accurate profiles of atmospheric temperature and water vapor. They will also monitor cloud water vapor and precipitation. All of these observations contribute to improved measurement of surface temperature and moisture. Other EOS instruments will provide complete hemispherical coverage of the radiance pattern to provide data for new angular distribution models, improved fluxes and daily, global observations of stratospheric and tropospheric aerosol optical thicknesses.

These figures show results from the Earth Radiation Budget Experiment for January 1986 and include the combined effect of sunlight and infrared radiation. The smaller figure shows the net radiation for clear-sky conditions, where blue (magenta) represents the net heat loss (gain) corresponding to the Northern (Southern) Hemisphere winter (summer). In the larger figure, clouds have a net cooling (heating) effect in the blue-green (yellow-red-magenta) regions.





Clouds play a critical role influencing the heat balance of the Earth. While high clouds can have a net heating effect, increasing the potential greenhouse effect, low clouds can do just the opposite. The study of clouds will thus be a central element in the Global Change Research Program.

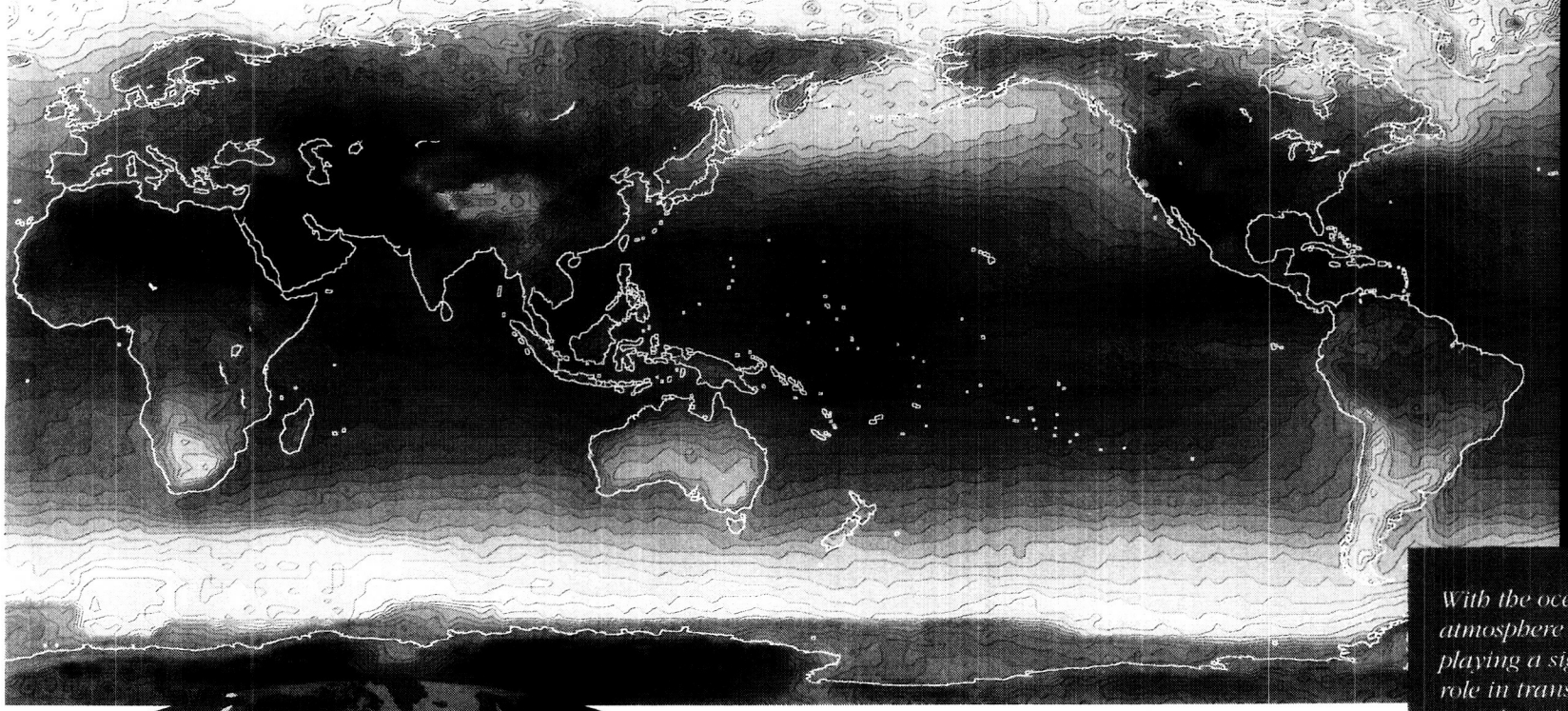
How Is Heat Transported?

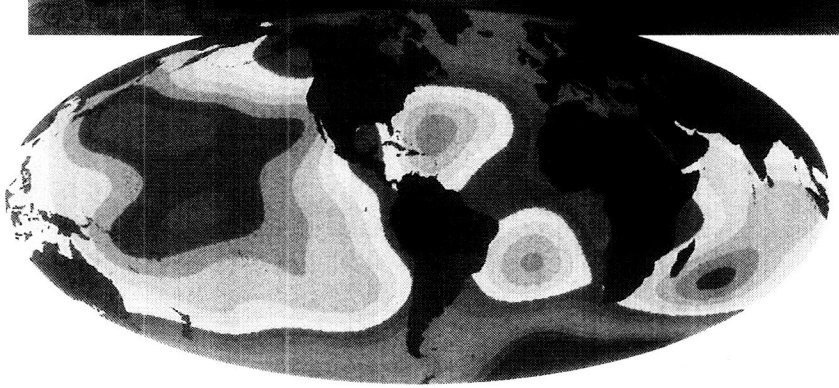
Atmospheric and oceanic circulations play a central role in the climate of the Earth. The atmosphere is driven by the radiation from the sun. The surface winds drive the oceanic circulation and influence the exchange of heat between the oceans and the atmosphere. The result is a complex interacting system of winds and currents which are a part of the climate system. As we try to understand and predict changing climate, improving our knowledge about the interaction between oceanic and atmospheric circulation is essential. For example, the heat content and time scales of motion in the oceans are larger than in the atmosphere. Thus, changing the storage of heat or the rate of formation of cold deep water in the oceans could substantially lessen the impact of a greenhouse effect. Similarly, the formation of sea ice in the polar regions can lead to changes in heat transport and deep-water formation which can have significant impacts on climate.

The best estimates of the heat flux by the atmosphere and oceans have been obtained by inference from the global radiation budget and atmospheric heat transport. Using these estimates, the oceans and atmosphere are found to transport roughly equal amounts of heat poleward. However, attempts to measure the oceanic heat transport directly have not succeeded in providing an accurate estimate. For many parts of the globe, particularly in the Southern Hemisphere, neither the magnitude nor the direction of the directly estimated heat transport is consistent with the inferred transport.

EOS, together with *in situ* measurements, will provide for the first time the necessary simultaneous observations for accurate estimation on a global scale of both the circulation and heat transport of the atmosphere and oceans. While operational satellites have given profiles of atmospheric temperature for almost two decades, EOS will provide the first simultaneous wind profiles on a global basis, which will improve estimates of the atmospheric heat transport. Similarly, the sea-surface temperature, sea-ice coverage, and surface oceanic circulation will be observed simultaneously by the radiometers and altimeters on EOS, leading to improved estimates of the heat exchange between the oceans and the atmosphere. By combining simultaneous observations from several EOS sensors, a better description of the complex interaction between the oceans and the atmosphere will be achieved. Coupled with numerical models, these measurements should greatly improve our ability to understand and predict the role of oceanic and atmospheric circulation in our changing climate.

The mean surface temperature (top) for June 1988 as obtained from the infrared and microwave radiometers (HIRS/MSU) aboard the NOAA series of meteorological satellites (increasing from blue-yellow to red). In the lower figure, the mean dynamic topography obtained from the Geosat satellite shows the large-scale average ocean circulation; streamlines are clockwise around the higher elevations (yellow-red) in the Northern Hemisphere.





With the oceans and atmosphere each playing a significant role in transporting heat from low to high latitudes, it is important to understand the nature of their circulations, as well as how they are driven and interact, so that their influence on regional and global climate can be assessed.

What Governs Rainfall Patterns?

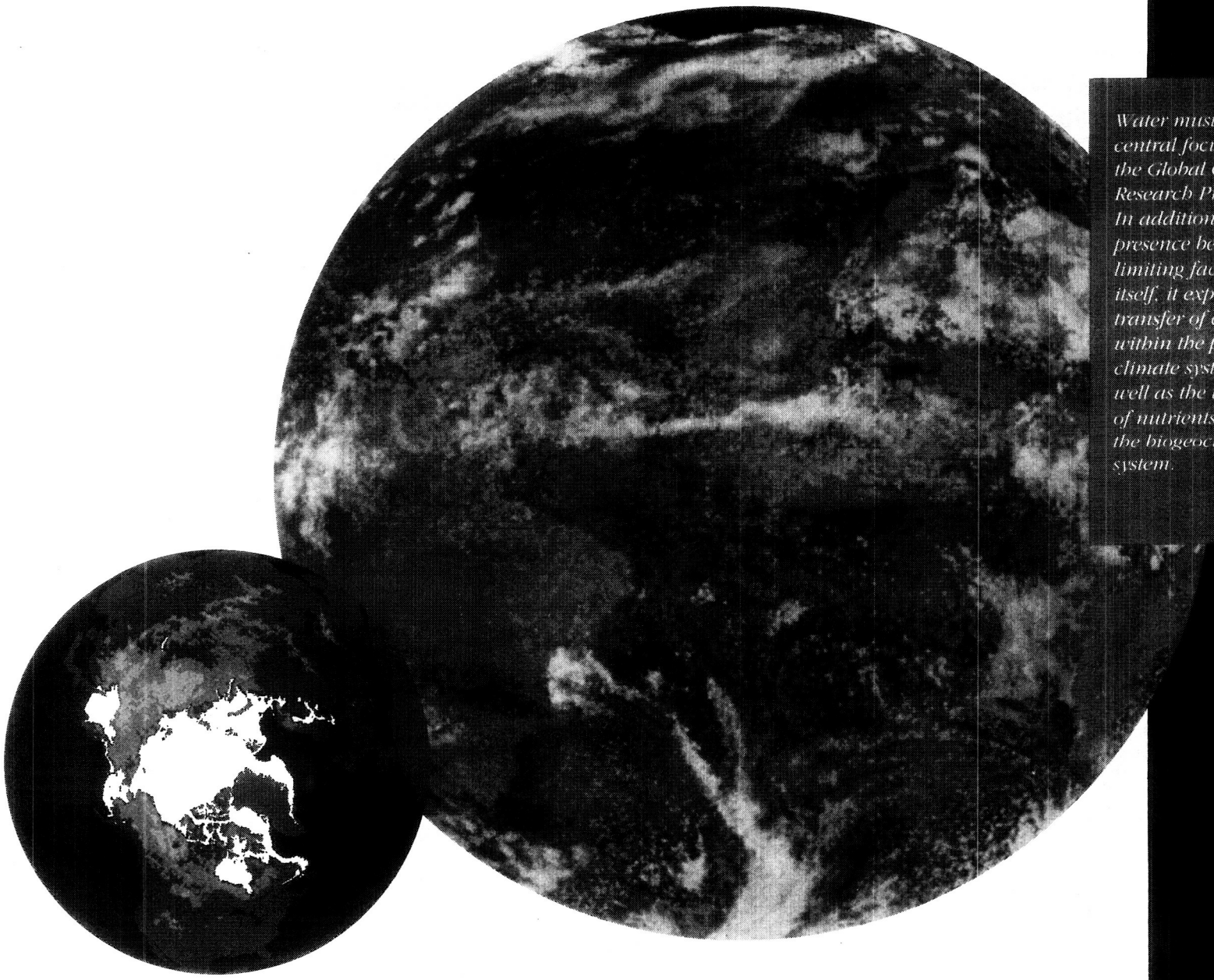
The existence of abundant water, an essential ingredient for life, is a primary difference between Earth and the other planets. Through the hydrologic cycle, water is an essential element of most processes that determine global climate change. The redistribution of heat that governs the Earth's climate depends largely on the transport, evaporation, condensation, and freezing of water, as well as the role of clouds and water vapor in the Earth's radiation balance. Water is a primary agent in shaping the landscape and in transporting sediments and nutrients. It is an essential part of all biogeochemical cycles and interacts strongly with vegetation. In the form of ice and snow cover, water affects the Earth's radiation balance, polar oceans, and sea level. Water supply governs the distribution and level of agriculture, energy production, and industry. Drought and floods are evident examples of the impact of water on societies. Despite the significance of water, our knowledge of the hydrologic cycle as part of the global, interacting system is meager.

In tropical and subtropical regions, clouds and precipitation are a major driving force for the circulation of the atmosphere. The Tropical Rainfall Measuring Mission (TRMM) and the efforts to establish a global precipitation climatology are the first steps in investigating one of the least known and most crucial elements of the global hydrologic cycle. But we are far from understanding how the hydrologic cycle will respond to a changing Earth system, or how water will influence the other components of the system.

Precipitation, soil moisture, atmospheric water vapor, clouds, snow pack, sea ice, polar glaciers, vegetation, temperature, and winds are each critical quantities needed to characterize the climate and hydrologic system. The very diversity of the effects of water in the Earth system have limited the development of a unified understanding of water. EOS will provide the first long-term, consistent global measurements of many of these key physical variables. The most important contribution of EOS will be the capability for simultaneous measurements necessary to investigate the processes which define the interactions and feedbacks within the hydrologic cycle.

A variety of EOS instruments will each contribute different components to our knowledge of physical climate and the hydrologic cycle. The global measurements and the process studies based on the simultaneous combination of EOS measurements are critical to understanding the central role of water in the Earth system.

This composite view (top) in the visible portion of the spectrum is based on data from NOAA's GOES-5 and European Meteosat-2 on July 4, 1983. Clouds are shown in greys, oceans blue, and land green to tan. Nimbus-7 microwave radiometer-derived estimates (bottom) of sea ice and snow cover for February 1983. Sea ice is white, permanent ice sheets purple, and depth of snow cover shades of blue.



Water must be a central focus in the Global Change Research Program. In addition to its presence being a limiting factor for life itself, it expedites the transfer of energy within the physical climate system, as well as the transport of nutrients within the biogeochemical system.

What Controls Atmospheric CO_2?

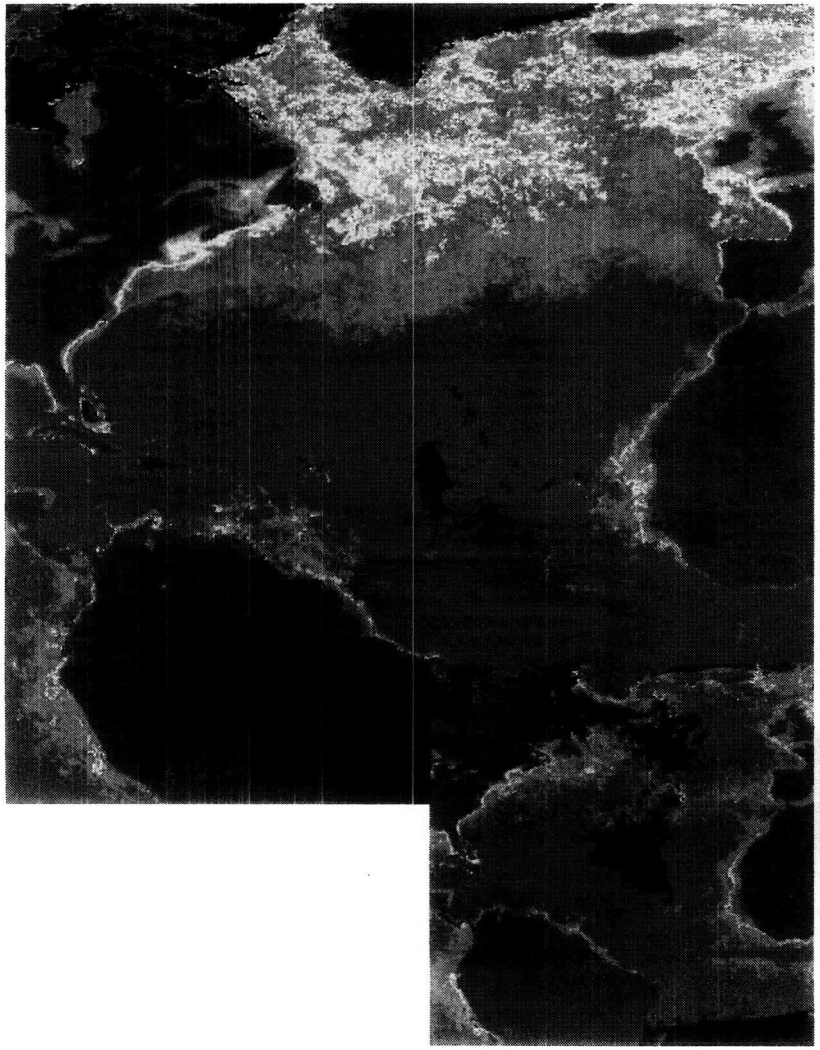
Since 1850, atmospheric carbon dioxide has increased by 25 percent and atmospheric methane by more than 100 percent. Though the changing carbon cycle has been studied for a long time, we remain uncertain about many of the controlling processes and the relative role of the terrestrial ecosystem versus the oceans in sequestering carbon. Hence we cannot predict future trends and effects. The exchange of carbon between the atmosphere, terrestrial biosphere, and oceans as well as the magnitude of the major carbon reservoirs are central issues in understanding the global carbon cycle. If climate changes, how will these exchanges be affected? Will the oceans take up less carbon dioxide or more? Will the terrestrial feedbacks be positive or negative? What will happen to the major storage reservoirs of carbon? These are vital issues for society.

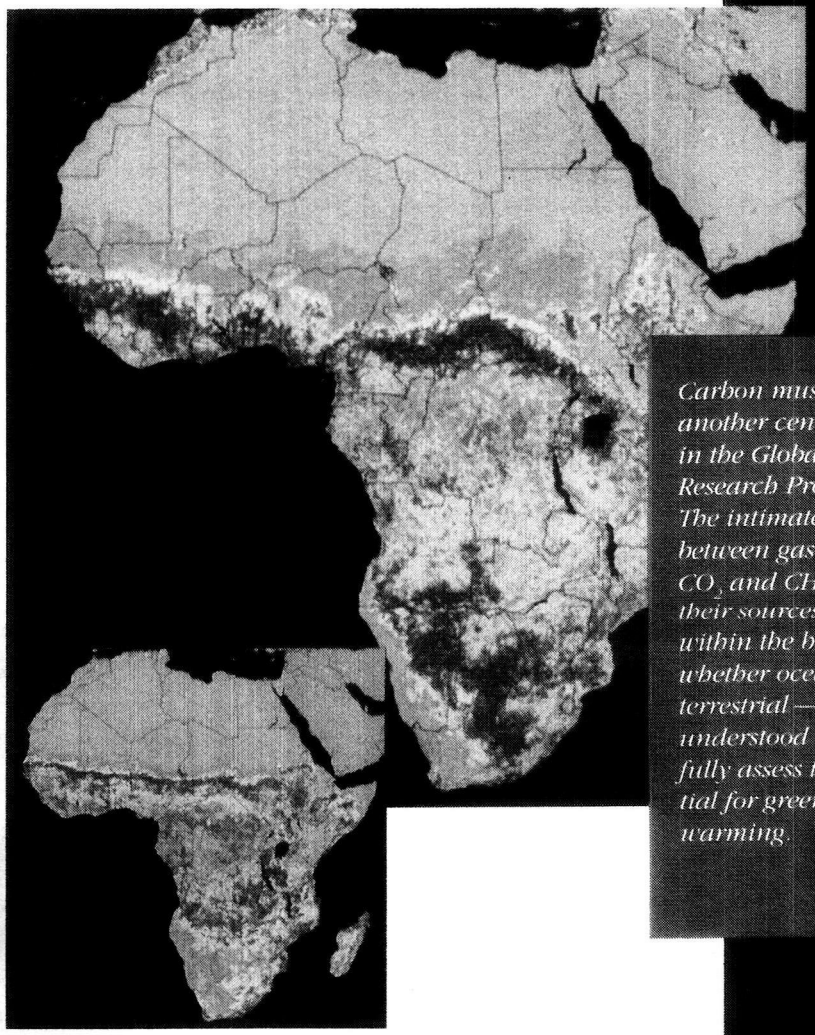
Large uncertainties in our understanding of the carbon cycle are related to questions such as: How much carbon dioxide is being released from vegetation and soils as a result of natural changes and deforestation? How much carbon dioxide is being taken up by the oceans? What is the rate of carbon transfer between the atmosphere and terrestrial ecosystems? The sources for increased methane emissions to the atmosphere need to be identified and quantified.

Current operational observing systems can provide estimates of the rate of deforestation, but coverage is incomplete because of cloud cover problems in the tropics. These systems have extremely restricted spectral resolution and cannot discriminate subtle changes in disturbed ecosystems. EOS instruments will provide needed global coverage of ecosystem states. The synthetic aperture radar, planned to fly on a separate spacecraft, will have the ability to penetrate clouds and forest canopies to characterize forest biomass and moisture status with high resolution maps. This information will be used to infer global productivity patterns, both on the land and in the ocean, another important aspect of the global carbon cycle.

The net flux of atmospheric carbon dioxide into the oceans remains uncertain. The rate of carbon uptake by the oceans is controlled by a complex interaction of ocean biology, chemistry, and circulation. Over 99 percent of all biologically incorporated carbon is buried in ocean sediments. Thus, small changes in oceanic primary productivity can have a major impact on the partitioning of carbon dioxide in the global carbon cycle. EOS instruments will allow dramatically improved estimates of biological activity in the upper ocean, the sea-surface state, and the circulation. The data will be used to make improved models of the carbon cycle.

The figures on the right compare 1989 March (top) and October (bottom) vegetation index patterns (increasing from tan to purple) based on data from the NOAA AVHRR. The figures on the left compare 1979 spring (top) and winter (bottom) phytoplankton chlorophyll concentrations (increasing from purple to yellow-red) based on data from the Nimbus-7 CZCS.





Carbon must be another central focus in the Global Change Research Program. The intimate linkages between gases, such as CO_2 and CH_4, and their sources/sinks within the biosphere — whether oceanic or terrestrial — must be understood in order to fully assess the potential for greenhouse warming.

How Is The Atmosphere Changing?

The changing chemical composition of the atmosphere in recent years has been a dramatic signal of global change. The principal changes observed have been the reduction of stratospheric ozone by chlorofluorocarbons and the buildup of greenhouse gases in the lower atmosphere.

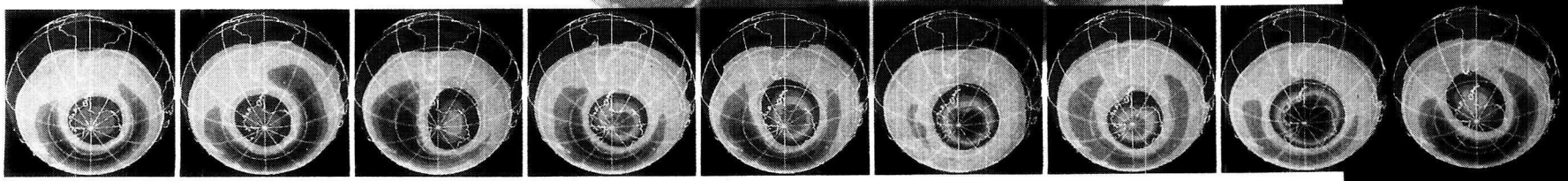
The chemistry of the atmosphere is central to understanding these critical environmental processes, and ozone is at the center of atmospheric chemistry. Ozone is a protective shield in the stratosphere and it is being depleted by reactions with chemicals, such as chlorofluorocarbons, which are released at the surface and transported to the stratosphere. In the troposphere, ozone is a pollutant gas from fossil fuel and biomass burning and from industrial activity. As global air quality degrades, the ability of the atmosphere to cleanse itself chemically is reduced. This in turn could enhance the greenhouse effect by increasing the accumulation of greenhouse gases.

Monitoring ozone depletion in the stratosphere and increase in the troposphere are key requirements of a Global Change Research Program. Measurements of global ozone concentrations as a function of altitude are required along with measurements of the global distribution of the atmospheric chemicals, dynamic processes, and solar energy input that control ozone concentrations. Global-scale models that couple chemistry and dynamics must be used to put the observations into a coherent picture of the atmosphere that allows confident projections of ozone depletion and greenhouse gas buildup for realistic emission scenarios.

UARS will provide focused data on stratospheric chemistry and dynamics in the early 1990s. The Total Ozone Mapping Spectrometer (TOMS), flown as an Earth Probe, will provide data on total ozone to the mid- to late-1990s. After that time, instruments on EOS and NOAA satellites will continue to watch stratospheric ozone depletion and to provide direct global-scale measurements of ozone and greenhouse gases.

EOS includes with its payloads the instruments necessary to study the global processes which control the stratospheric ozone layer and to monitor changes in tropospheric gases. The 15-year life of EOS will allow measurement over a sufficiently large number of annual cycles, biennial oscillations, and ozone changes, to greatly improve our understanding of the ozone layer. It will have the capability to monitor the long- and intermediate-lived chemical components of the troposphere and their long-term changes. The EOS instruments will thus address the central problems of the relation of climate to changing atmospheric chemistry.

The reduction of "protective" ozone in the stratosphere via man-made chemicals such as chlorofluorocarbons, as well as the increase of "harmful" ozone in the troposphere as a result of pollution, point to the need to understand atmospheric chemistry as a key element of the Global Change Research Program.



What is the Role Of The Solid Earth?

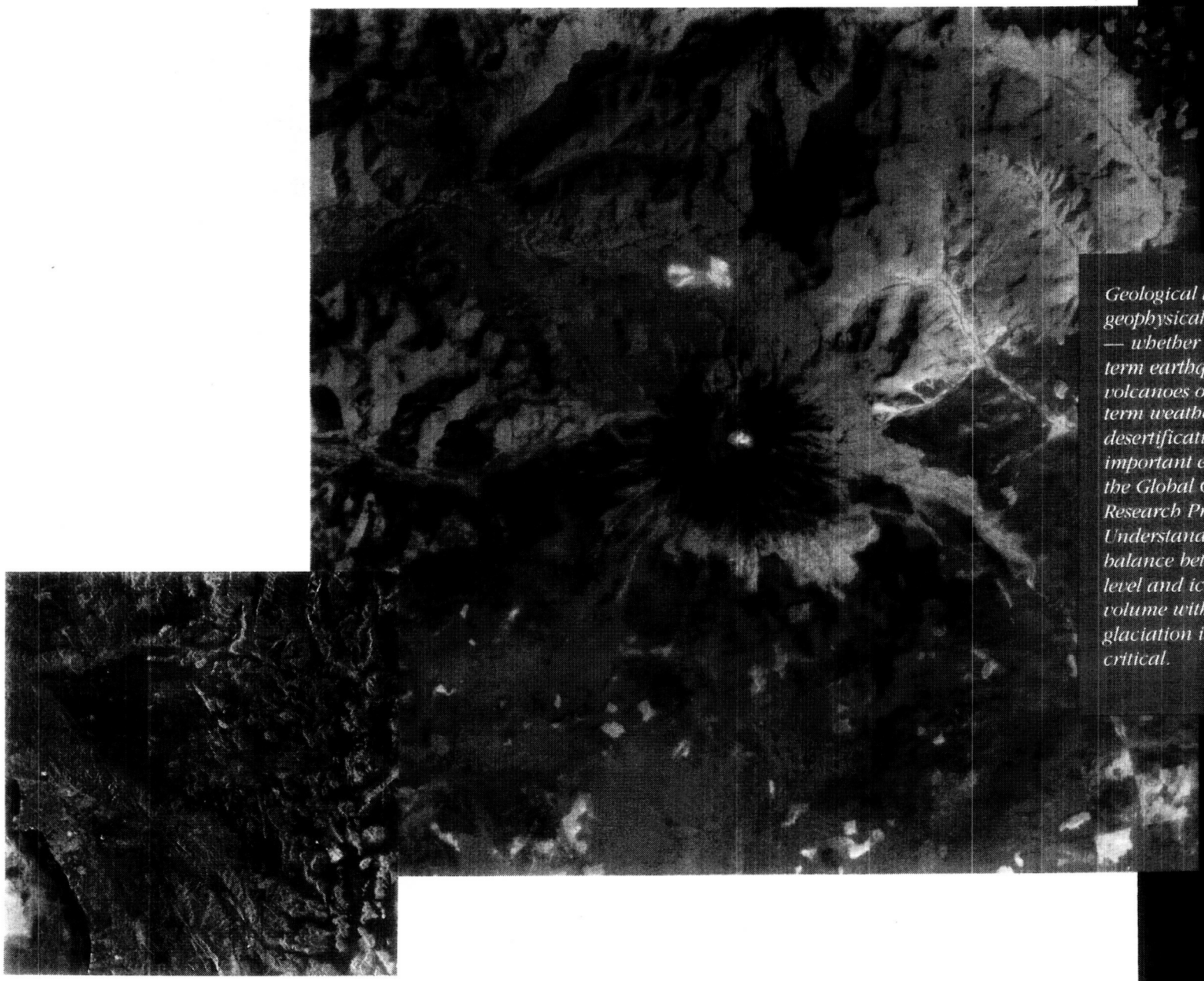
Geological and geophysical processes vitally affect life on Earth. The spectacular hazards of volcanic eruption, earthquakes, floods, and landslides are familiar to all who follow the world news. Volcanoes introduce chemicals and aerosols into the atmosphere. Crustal movement results in earthquakes, regional sea-level variations, and potential flood hazards. Changes in the massive amounts of ice now stored in glaciers and polar ice caps could lead to significant changes in sea level and oceanic circulation. Desertification and erosion of large tracts of land affect the global hydrologic cycle and Earth's productivity. The motion of material deep in the core and mantle causes subtle changes in Earth's rotation and length-of-day in ways that are not yet well understood.

Understanding these processes requires a diversity of observations. We need to monitor the gaseous effusion and thermal productivity of volcanoes to gauge atmospheric effects and to assess the likelihood of eruption and potential of resultant hazards. EOS atmospheric and land-surface sensors will be used to characterize the composition and nature of volcanoes. Altimeters and positioning systems will be used to detect expansion of probable hazardous volcanoes.

We need to monitor the mechanisms of plate motion over long periods and during short, drastic events. Densely spaced, high resolution geodetic measurement on a frequent basis is the most likely technique to achieve timely earthquake prediction. High resolution geodetic observation and altimetry are also the keys to understanding regional uplift, subsidence, and associated hazards in coastal areas, as well as change in the shape and volume of polar ice caps. Changes in the Earth's rotation and length-of-day are best monitored using high resolution geodetic techniques, while the deep-seated processes in the Earth which cause these changes are best understood by study of the Earth's magnetic field. We must be able to detect areas of current or potential desertification and erosion, which requires large-scale observation and detailed characterization, and the ability to continually update the observations.

EOS will provide the sensors required to document and understand the interactions between geological and geophysical processes and other components of the Earth system. The diversity of simultaneous observations which will be possible from the EOS platforms will allow timely responses to situations which would not have been possible with earlier techniques. The remote sensing aspects minimize risk of human life in documenting extreme events.

Mineralogical and thermal features in the vicinity of Mt. St. Helens based on data from Landsat Thematic Mapper in July 1984, four years after its last eruption; note the "hot spot" in the crater, as well as on the flank of the volcano. The black and white image (315 km square) from Seasat's synthetic aperture radar in 1978 shows surface features in Southern California, including the area where the San Andreas and Garlock Fault Zones converge.



Geological and geophysical processes — whether shorter term earthquakes and volcanoes or longer term weathering and desertification — are important elements in the Global Change Research Program. Understanding the balance between sea level and ice-sheet volume with changing glaciation is also critical.

Gathering Comprehensive Global Observations

A new start is proposed for EOS in NASA's FY 1991 budget submission to Congress, with development to be initiated in October 1990. NASA began conceptual studies for EOS in 1982; coordination with the European Space Agency (ESA), Japan, and Canada was initiated in 1986. Present plans call for two series of polar-orbiting platforms: EOS-A and EOS-B. The 15-year observational period will be achieved using three identical satellites per series, each with a five-year design lifetime.

ESA is planning two series of polar platforms with a climatological and terrestrial focus, respectively, and Japan is planning one polar platform. Both NASA and NOAA sensors are planned for inclusion on these platforms. Additionally, NASA is planning to provide sensors as attached payloads for the Space Station.

A group of 41 sensors from the U.S., Canada, Japan, and Europe has been selected as candidates for flight on EOS. The EOS-A series is tentatively planned to focus on atmospheric sounding and surface imaging; selection of specific sensors will be in October 1990. The EOS-B series is planned to include sensors capable of extending observations made by the UARS and TOPEX/Poseidon missions; sensor selection for EOS-B will occur one year later.

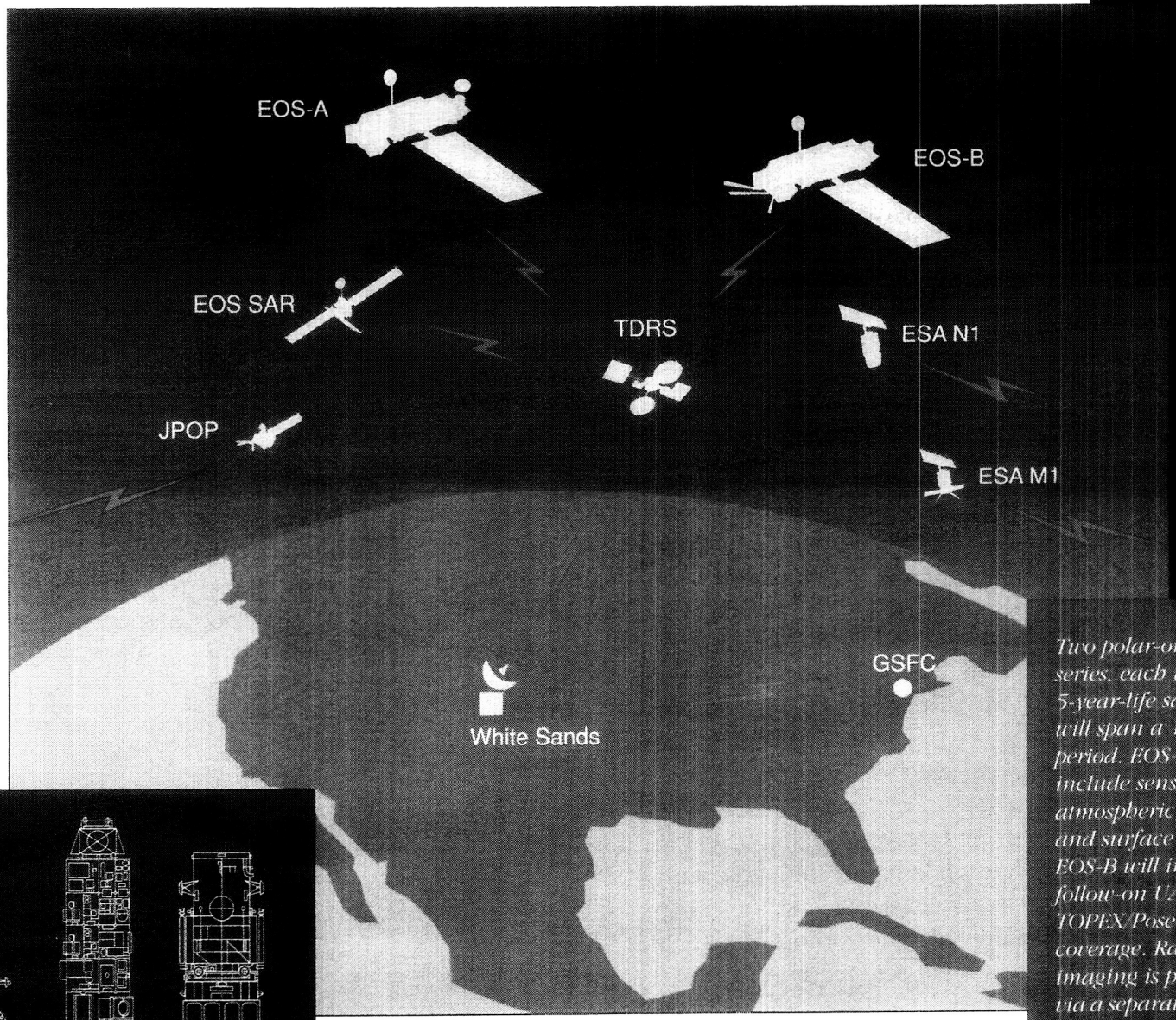
Platform size for EOS has been chosen to accommodate atmospheric sounding and surface imaging sensors, a grouping which maximizes the synergistic use of coincident observations, as well as minimizes atmospheric induced uncertainties. The satellites will be launched into polar orbit from Vandenberg Air Force Base on Titan-IV rockets.

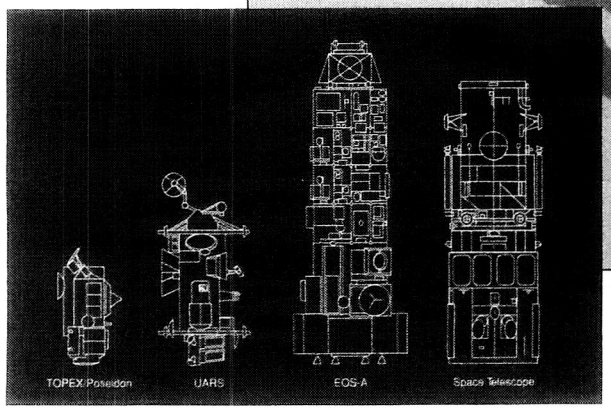
An EOS platform will accommodate a payload up to 3500 kilograms and can supply up to 3.2 kilowatts of power to the payload. This platform is twice the size of UARS and can supply about four times the power; it will accommodate two to four instruments more than the 10 aboard UARS. Because of the wider spectral range of the instruments, its data system will manage more than 10,000 times the data of UARS.

The need for global coverage every one to three days dictates a sun-synchronous orbit with a quasi-two-day repeat; a 705-kilometer altitude, 98.2-degree inclination orbit meets this need. It will have a 1:30 p.m. local equatorial-crossing time.

The Synthetic Aperture Radar (SAR), not able to be efficiently accommodated on the EOS series of platforms, is planned for flight on a dedicated satellite in 1999. Its orbit will have a 620-kilometer altitude and similar equatorial-crossing time; this will provide frequent opportunities for coincident observation of the same locations as sensors on EOS platforms.

NASA's Mission to Planet Earth includes the EOS-A and -B series of polar platforms, a separate EOS SAR mission, and the TDRS communication link; not shown are the Space Station attached payloads and Earth Probes; related foreign polar platforms include the ESA M-1 and N-1 series, as well as the Japanese JPOP. The smaller image shows a comparison of launch-configuration sizes with EOS-A at a 14.8-meter height.





Two polar-orbiting series, each with three 5-year-life satellites, will span a 15-year period. EOS-A will include sensors for atmospheric sounding and surface imaging; EOS-B will include follow-on UARS and TOPEX/Poseidon coverage. Radar imaging is planned via a separate EOS SAR.

Providing Easy Access To Data

The EOS Program has put a major emphasis on the Data and Information System (EOSDIS). EOSDIS is planned to acquire a comprehensive, global, 15-year data set; to maximize the utility of this data set for scientific purposes; and to facilitate its easy access by the research community. In addition to data processing, archival, and distribution facilities, EOSDIS includes the necessary capabilities for command and control of the spacecraft.

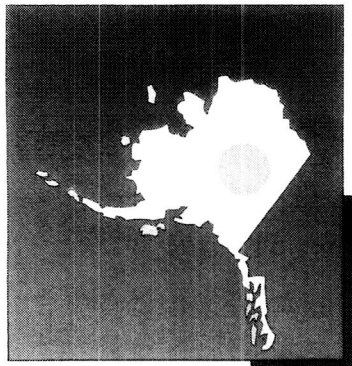
The development of EOSDIS will be initiated immediately by building on the existing infrastructure within the research community. It will implement an architecture which is open and distributed, so that it can evolve with advances in computing and networking technology. The near-term objectives are to support the research and analysis of data which both exist and will come from the near-term pre-EOS missions. In this way, the research community can gain valuable early experience in preparation for the future large EOS data volume.

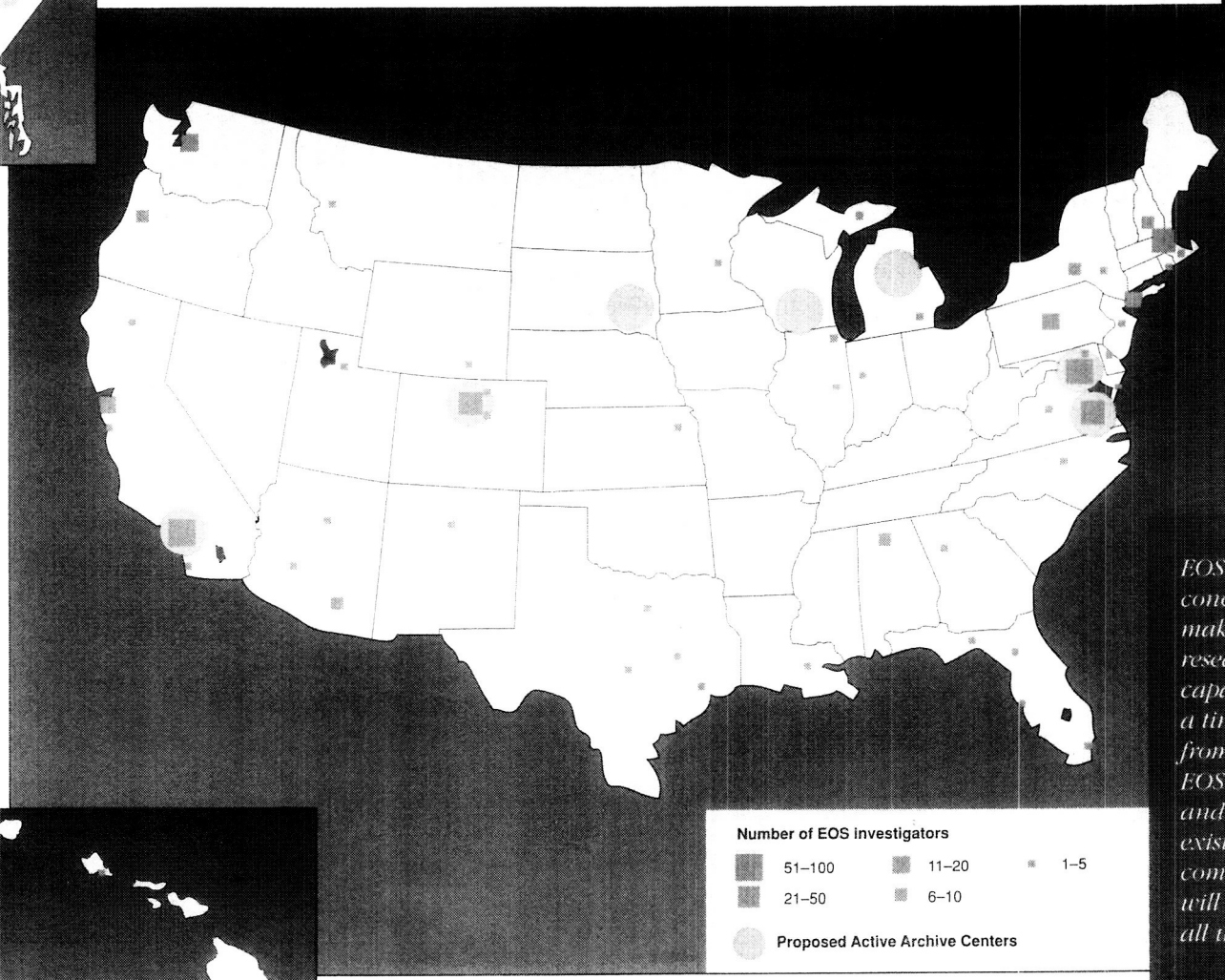
Archived data sets, in addition to those from the EOS satellites, will include complementary *in situ* and satellite data. EOSDIS will also involve the U.S. Geological Survey, National Oceanic and Atmospheric Administration, the National Science Foundation and other agencies.

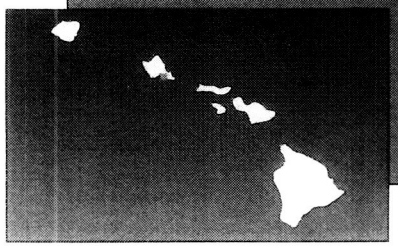
There will be two types of data products: standard and specialized. Standard products will be generated and archived at Active Archive Centers; the target time for the availability of engineering-level products is within 48 hours of collection; the target for derived geophysical products is within 96 hours. Specialized products will be generated by individual investigators and made available to EOSDIS for archiving and distribution, as appropriate.

The EOSDIS policy specifies that all data and derived products be available to all users, with no preference given to EOS investigators. Research users in the U.S. and participating countries will pay only the nominal cost of data reproduction and delivery; they will be required to agree to publish their results and to make available supporting information, including methods for analyzing data. Research users in other countries may propose cooperative projects and associated "in kind" contributions (i.e., provide similar access to appropriate satellite, aircraft, and surface-based data) in exchange for access to EOS data on similar terms. Access to the raw data stream will be provided to operational agencies for forecasting purposes. NASA will provide for the commercial distribution of data on a non-discriminatory basis to all other users.

The distribution of the U.S. EOS investigators, shown along with proposed sites under consideration as EOSDIS Active Archive Centers (Goddard Space Flight Center, Jet Propulsion Laboratory, Langley Research Center, National Snow and Ice Data Center, National Center for Atmospheric Research, University of Alaska, University of Wisconsin, and Michigan Consortium for International Earth Science Information Network).







EOSDIS represents a concerted effort to make available to the research community a capability to access in a timely manner data from the EOS mission. EOSDIS will build on and evolve from the existing efforts in the community. All data will be available to all users.

Predicting Global Change

Our planet is experiencing profound environmental changes; the economic and social consequences of global change have received attention at the highest governmental levels. To document, understand, and predict global change is a major scientific challenge; but up to now we have lacked the ability to provide the necessary comprehensive information for key policy decisions. Modern technology and new insights offer hope for early warning of change and accurate predictions of future change, and thus major societal benefits.

Mission to Planet Earth, building on precursor research missions and encompassing the proposed Earth Probes and the Earth Observing System, is a major NASA contribution to the U.S. Global Change Research Program. It will provide the necessary comprehensive global observations of Earth which will reveal how the processes that govern global change interact as part of the Earth System. This understanding is critical to the development of models for predicting future environmental change. With a continuing, comprehensive data set from EOS, it will be possible to update and enhance the models so that they can provide the vital information needed about environmental change on local, regional, and global scales.

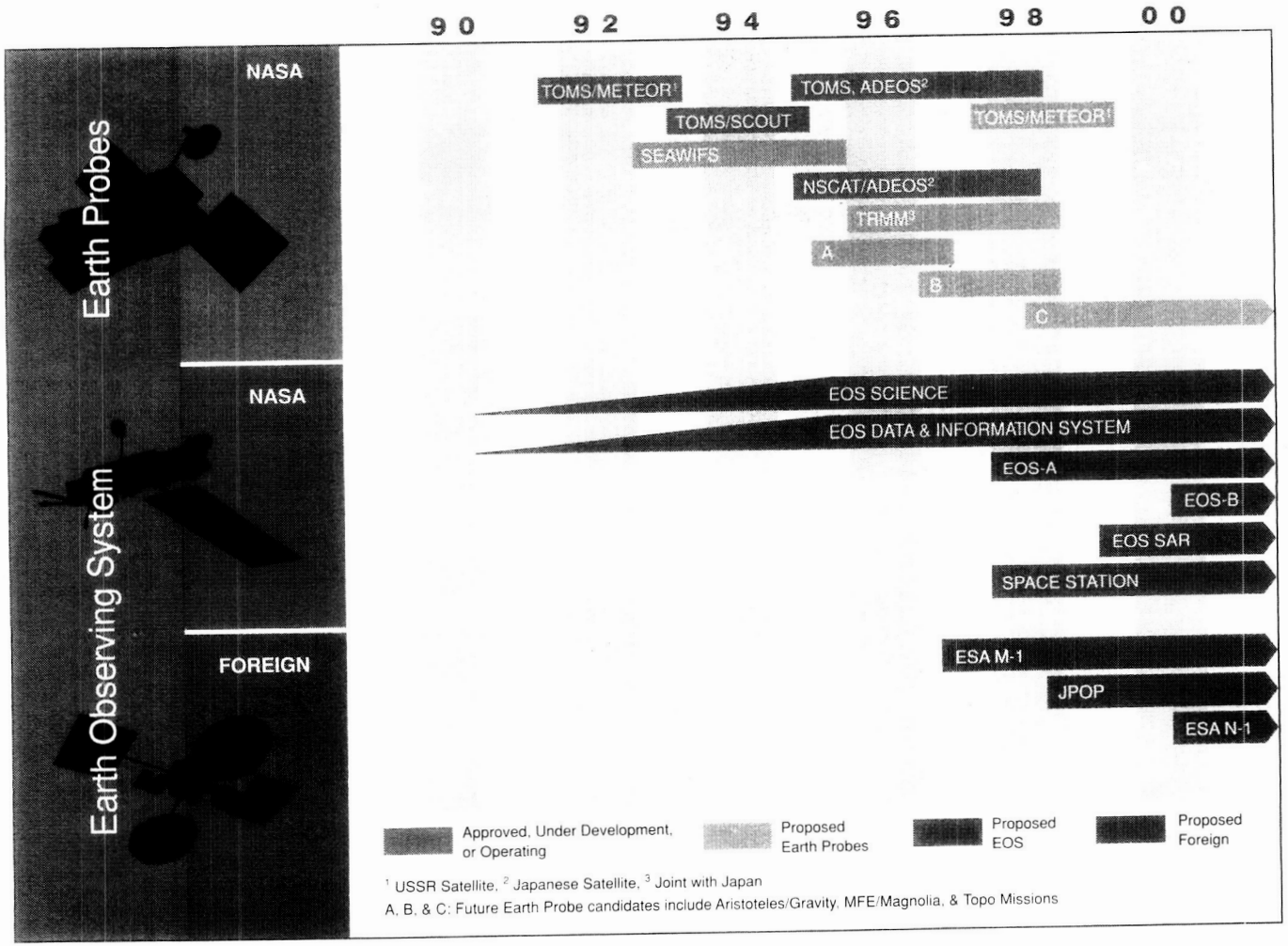
Our nation must take the lead in providing sustained observations of the Earth. We have the scientific and technical capability; our national aspirations and spirit demand that we rise to this challenge.

The total cost of EOS is estimated to be 17 billion dollars through the year 2000. The cost of EOS platforms and payloads is commensurate with other large observing programs, such as the four Great Observatories of NASA's Astrophysics Program.

Typically with flight programs, NASA has allocated about 70 percent of the funding for spacecraft hardware and 30 percent for ground-based activities. For EOS, in recognition of the large data volume and the need for a comprehensive science program, NASA will allocate 40 percent for spacecraft hardware and 60 percent for ground-based activities, including EOSDIS and science.

Although the cost of such an observing and data system is large, it is small compared to that of taking no action or acting on incomplete information. Considering the consequences of global change for humankind, we cannot afford to do less. Mission to Planet Earth will enable us to observe, understand, and predict change on Planet Earth.

This table shows the distribution of the proposed Earth Probes, EOS, and related foreign missions. Near-term activities include the initiation of the EOS science and Data and Information System activities.



Given the long-term, comprehensive data set from EOS, as well as complementary in situ observations, it should be possible to document global change, understand relevant processes, and build improved models. The ultimate goal is the development of realistic predictive models.

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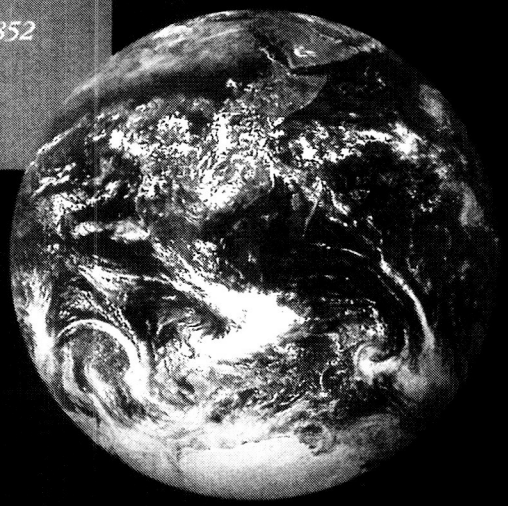
"This we know: the Earth does not belong to man, man belongs to the Earth. All things are connected like the blood that unites us all. Man did not weave the web of life, he is merely a strand in it. Whatever he does to the web, he does to himself."

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