Earth System Science: Overview: A Program for Global Change (1986)

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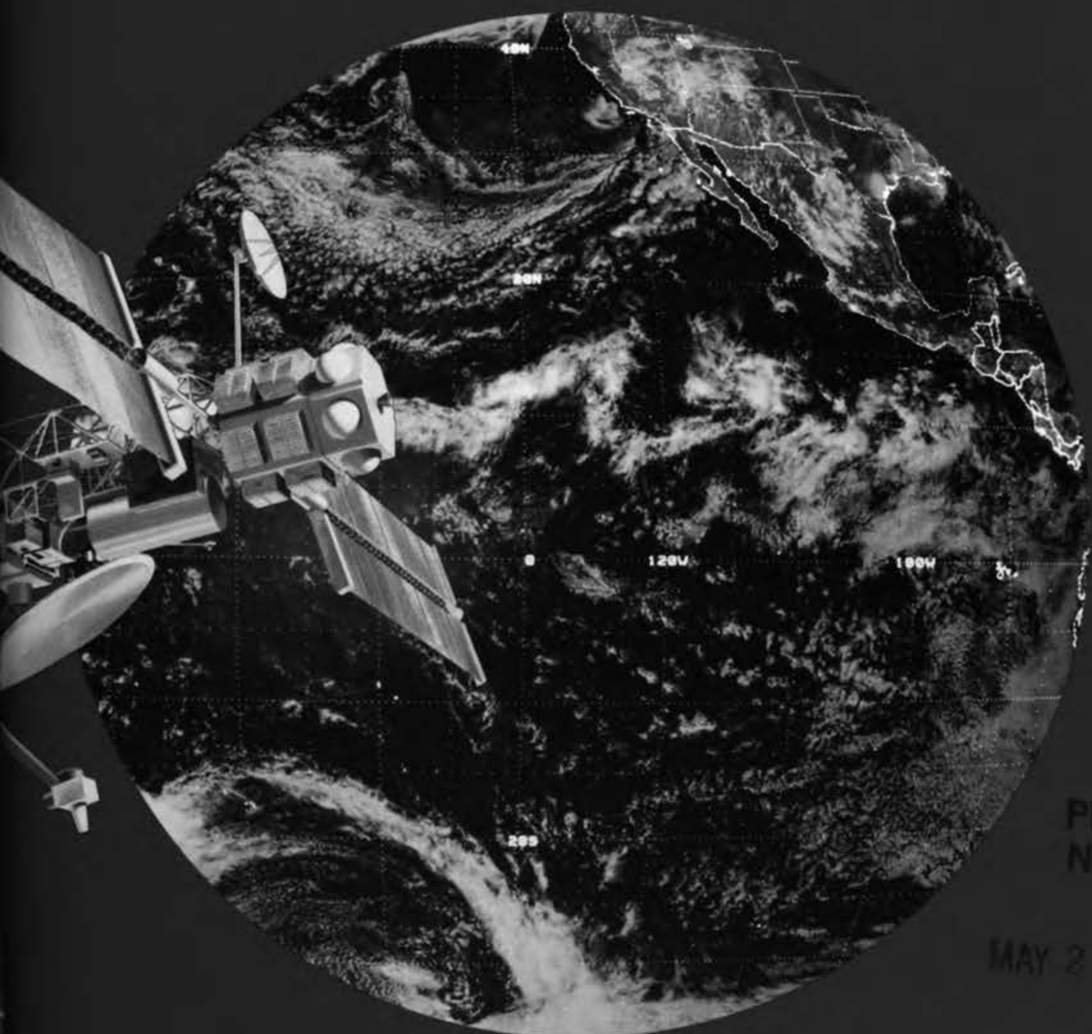
Earth System Sciences Committee; NASA Advisory Council

Earth System Science
Overview

A PROGRAM FOR GLOBAL CHANGE



Prepared by the
Earth System Sciences Committee
NASA Advisory Council

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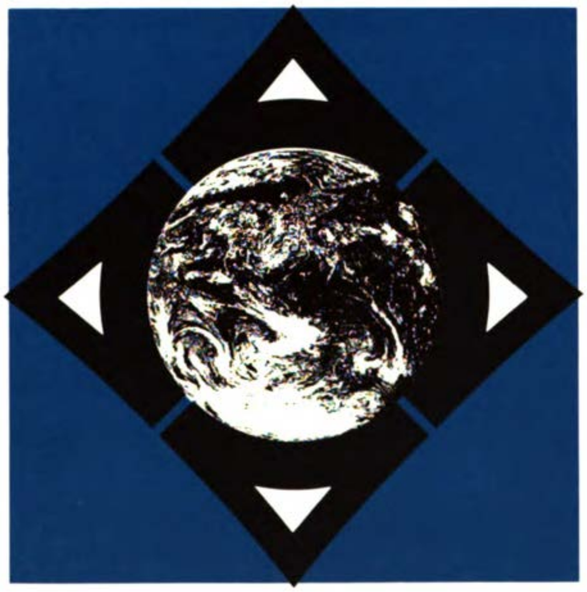

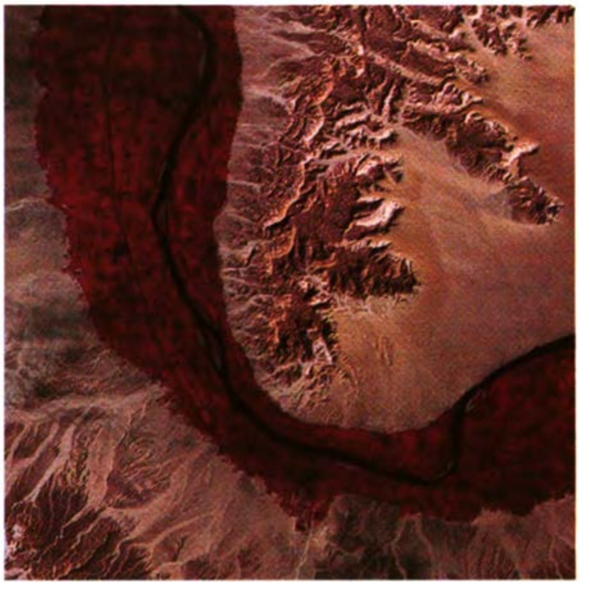

Introduction

The Goal of Earth System Science

To obtain a scientific understanding of the entire Earth System on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all timescales.

The Challenge to Earth System Science

To develop the capability to predict those changes that will occur in the next decade to century, both naturally and in response to human activity.

Scientific research continues to yield fundamental new knowledge about the Earth. Studies of the continents, oceans, atmosphere, biosphere, and ice cover over the past thirty years have revealed that these are components of a far more dynamic and complex world than could have been imagined only a few generations ago. These investigations also have delineated, with increasing clarity, the complex interactions among the Earth's components and the profound effects of these interactions upon Earth history and evolution. We can now proceed, for example, to incorporate the global effects of atmospheric wind stress into models of oceanic circulation; to study volcanic activity as a link between convection in the Earth's mantle and worldwide atmospheric properties; and to trace the global carbon cycle through the many transformations of this vital element by terrestrial and ocean biota, atmospheric chemistry, and the weathering of the Earth's solid surface and soils.

Our new knowledge is providing us with deeper insight into the Earth as a system. This insight has set the stage for a more complete and unified approach to its study, Earth System Science.

Complementing our innate curiosity about our planet, the search for practical benefits to improve the quality of human life has long provided a second important motivation for Earth science. Today, human beings in most regions of the globe enjoy greater abundance from the Earth than at any time in our history. Further advances in weather prediction, agriculture and forestry, navigation, and ocean-resource management will accompany a still better understanding of Earth processes.

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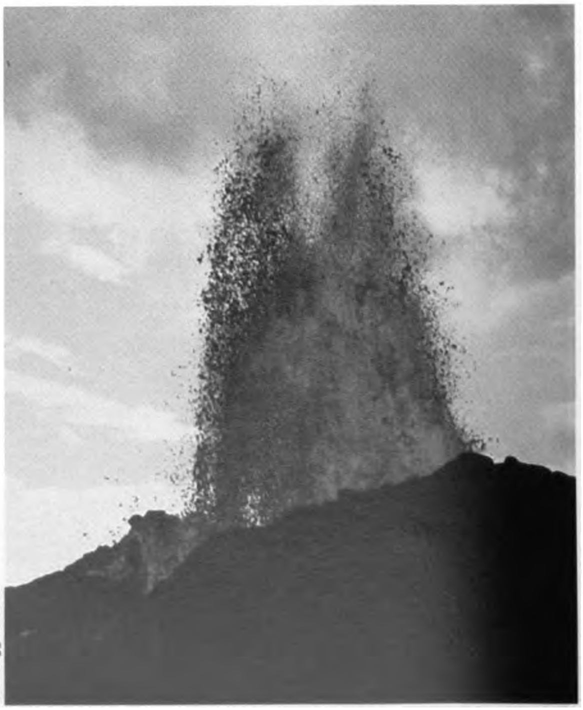

J.D. Griggs/USGS

Now a third and urgent factor spurs the quest for knowledge. The people of the Earth are no longer simple spectators to the drama of Earth evolution but have become active participants on a worldwide scale, contributing to processes of global change that will significantly alter our habitat within a few human generations. In some cases, such as the depletion of the Earth's energy and mineral resources, the effects of human activity are obvious and irreversible. In other cases, such as the alteration of atmospheric chemical composition, the processes of change are more difficult to document, and their consequences harder to foresee. Moreover, the global effects of many human-induced changes cannot readily be distinguished from the results of natural change on the same timescale.

We particularly require a set of Earth observations that will permit us to disentangle the complex interactions among the Earth's components and to document their effects over extended time periods. Such observations will allow us to establish causal relationships among the processes involved and therefore to distinguish between the consequences of human economic and technological activity, on the one hand, and the results of natural change on the other. With this new knowledge, we will then be able to take timely action to ensure an abundant Earth for future generations.

We can begin to meet this challenge today:

◆ **Programs of global observations** relevant to a number of Earth System properties have already been carried out with great success. Sensors for future space and *in situ* measurements are ready to deploy or in advanced stages of design. The most urgently needed observations can be made through near-term missions and programs that have been thoroughly planned and can now be initiated. The proposed Earth Observing System aboard polar-orbiting platforms now planned as part of the U.S. Space Station Complex appears to provide the most advantageous and cost-effective means of obtaining essential global observations from space from the mid-1990's onwards.

◆ **Information systems** specifically constructed to process individual sets of global data are already in operation. New developments in computing technology have now made feasible an advanced information system to provide worldwide access to these current data sets, to process the more extensive global data to be obtained in the future, and to facilitate data analysis and interpretation by the scientific community.

◆ **Existing numerical models** are already contributing to detailed understanding of individual Earth components. Building upon these prototypes, new conceptual and numerical models of the Earth System are now being developed to explore the interactions among the Earth's components and to analyze the global effects of physical, chemical, and biological processes. By furnishing a quantitative understanding of the Earth System, these new models will also provide predictions of the effects of global change on human populations.

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◆ **Federal agencies** are recognizing the need for interdisciplinary research support and interagency cooperation. Moreover, there is a developing consensus on the goals and missions of these agencies in Earth-science research, as exemplified by a recent report of the President's Office of Science and Technology Policy (see Appendix A).

◆ **A worldwide political awareness** of the necessity for a coordinated, international approach to the global study of the Earth has been created, and cooperative research efforts by many nations across the globe are under way.

If pursued with resolve and commitment, this research program will bring us rewards of knowledge as dramatic, and as relevant to humankind, as any in scientific history. The anticipated achievements of Earth System Science include the following:

◆ **Global measurements:** Establishment of the worldwide observations necessary to understand the physical, chemical, and biological processes responsible for Earth evolution on all timescales.

◆ **Documentation of global change:** Recording of those changes that will occur in the Earth System over the coming decades.

◆ **Predictions:** Use of quantitative models of the Earth System to anticipate future global trends.

◆ **Information base:** Assembly of the information essential for effective decision-making to respond to the consequences of global change.

Guided by this new knowledge, the Earth's human societies may wish to consider, for example, modifications in the use of fossil fuels; political, social, and technical planning for the relocation of primary grain-production areas; controls on the disposal of chemical wastes; or redistribution of water in response to drought forecasts.

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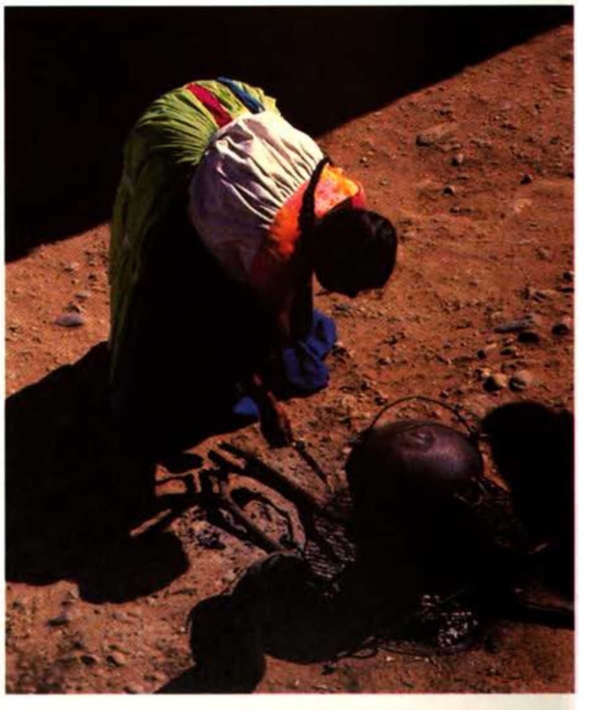

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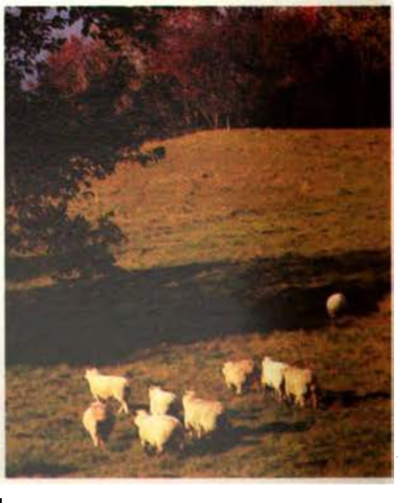

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We have no greater concern than the future of this planet and the life upon it. Exploration of the other planets in the Solar System has confirmed the very special place of our world among them: the only planet with a biosphere, the only planet with abundant oxygen and liquid water, and the only planet with plate-tectonic processes that renew its surface structure and recycle nutrients essential to life. To preserve it, we must continue to seek a deeper scientific understanding of global Earth processes. Now is the time to meet this challenge through a program of Earth System Science.

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Our Planet Earth

THE EARTH SCIENCES

For the present generation of human beings, the continuing search for new knowledge of our planet has been particularly exciting. In an extraordinary burst of research findings over the past 30 years, our view of the solid Earth has been totally transformed. The earlier notion of a static, placid globe has been swept away, replaced by the dynamism and drama of plate tectonics. Enormous sections of the Earth's crust, born at mid-ocean ridges, float upon the convective mantle of the Earth, restlessly jostling against neighboring plates until their ultimate subduction back into the Earth's interior along continental plate boundaries. Patterns of mountain-building, volcanism, and earthquake activity all fit consistently into this new view. Plate tectonics has, for the first time, provided a unified, coherent description of the Earth's crustal features.

The past several decades have also seen remarkable advances in our knowledge of the fluid Earth. The oceans, atmosphere, and ice-covered regions of the planet are now recognized to be closely coupled in shaping the Earth's weather and climate. Research has charted the courses of the world's great ocean currents and revealed the distribution of heat, salt, and nutrients in the ocean interior. Aided by satellite observations of global temperature, moisture, and cloud cover, scientists have constructed numerical models of the atmosphere that have begun to provide reliable predictions of general atmospheric circulation. Studies of the ocean-atmosphere interaction have identified an association between the El Niño ocean-current variation off the South American coast and the Southern Oscillation atmospheric pressure phenomenon that produces effects across the entire tropical Pacific Ocean and beyond. Such investigations are contributing to an initial understanding of the operation of the fluid Earth on a global scale.

The biological Earth is now recognized to exert a major influence on global processes. Ocean biota, for example, have an important effect on climate through net removal of atmospheric carbon dioxide during formation of ocean sediments. Both ocean biota and land ecosystems participate in the global cycles of chemicals essential to life. Furthermore, land biota can also affect climate through their important influence on albedo and water cycling, and through production and emission of various trace gases. All of these findings have established important connections among the components of the planet Earth and thus have emphasized the essential unity of global processes, which are only now beginning to be studied systematically.

SCIENCE FOR PRACTICAL BENEFITS

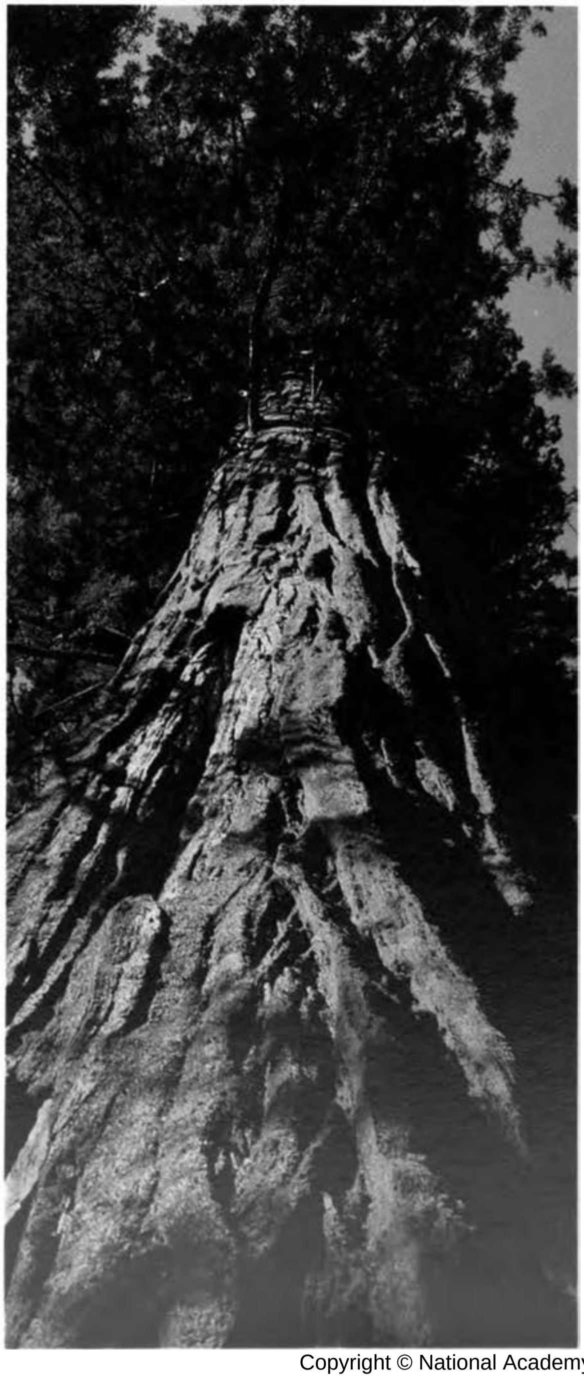
The pursuit of an improved quality of life upon the Earth goes hand in hand with the search for greater scientific understanding of the Earth itself. The application of basic research to human needs is today proceeding more vigorously than ever before.

One of the most important benefits secured to our generation is increasingly accurate global weather prediction. Numerical simulation of atmospheric processes began to become practical in the 1960's with the advent of high-speed computers. These simulations were accompanied by a complementary and dramatic new development: global observations of the Earth's surface and atmosphere from space, beginning with the launch of the first experimental satellite in 1960. The first operational series of polar-orbiting weather satellites began in 1966, and a series of geostationary environmental satellites became operational in 1974. These spacecraft have permitted continuous, global recording of temperature, cloud cover, and other atmospheric variables to supplement an increasingly refined series of measurements made from the ground and within the atmosphere itself. Regional weather forecasts are now based almost entirely upon the predictions of numerical models employing these data.

Studies of the land and the oceans have produced additional benefits for humanity within the past generation. Research into crustal movements and plate tectonics has delineated regions of potential volcanic and earthquake activity and has begun to develop predictors of these events. We have come to understand the origin and distribution of the Earth's vast quantities of petroleum, natural gas, and mineral deposits — particularly since the investigation of environment-specific processes, such as the deposition of metallic-sulfide ores at hydrothermal vents along oceanic spreading centers. Spacecraft observations of ocean color have identified plankton-rich regions and productive time periods important to the aquatic food chain, thus promising more efficient use of our fishing resources. Continued research holds the potential to increase still further the abundant benefits of the Earth.

A NEW HUMAN NEED: STUDY OF GLOBAL CHANGE

Human activity is now causing significant changes on a global scale within the span of a few human generations. The burning of fossil fuels, for example, is injecting carbon dioxide into the atmosphere at unprecedented rates. The atmospheric concentration of this gas has increased by nearly 25 percent since the Industrial Revolution, and by over 10 percent since 1958 alone; at this rate it will double within a century. Carbon dioxide is transparent to sunlight entering the atmosphere but blocks the flow of heat radiated outward from the Earth's surface, thus creating a "greenhouse effect" that produces a net warming trend. On the basis of the present rate of increase in atmospheric carbon dioxide, climate models predict an average global increase of at least 2°C in surface temperature during the next century — an increase comparable to that experienced since the last Ice Age 18,000 years ago — together with marked shifts in precipitation patterns. There are also continuing increases in a number of other "greenhouse gases," including methane, chlorofluorocarbons, and tropospheric ozone; although the concentra-



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tions of these trace species are presently much less than that of carbon dioxide, they are rising much more rapidly. Their effects can also be more pronounced: molecule for molecule, chlorofluorocarbons produce 10,000 times the greenhouse effect of carbon dioxide, in addition to depleting stratospheric ozone.

Moreover, the daily needs of nearly half the world's people for fuel and nourishment are reducing the Earth's vegetation and the productivity of marginal agricultural land. Because of these economic and cultural forces, the extent of the Earth's forest cover has decreased substantially since 1950. Since much of the

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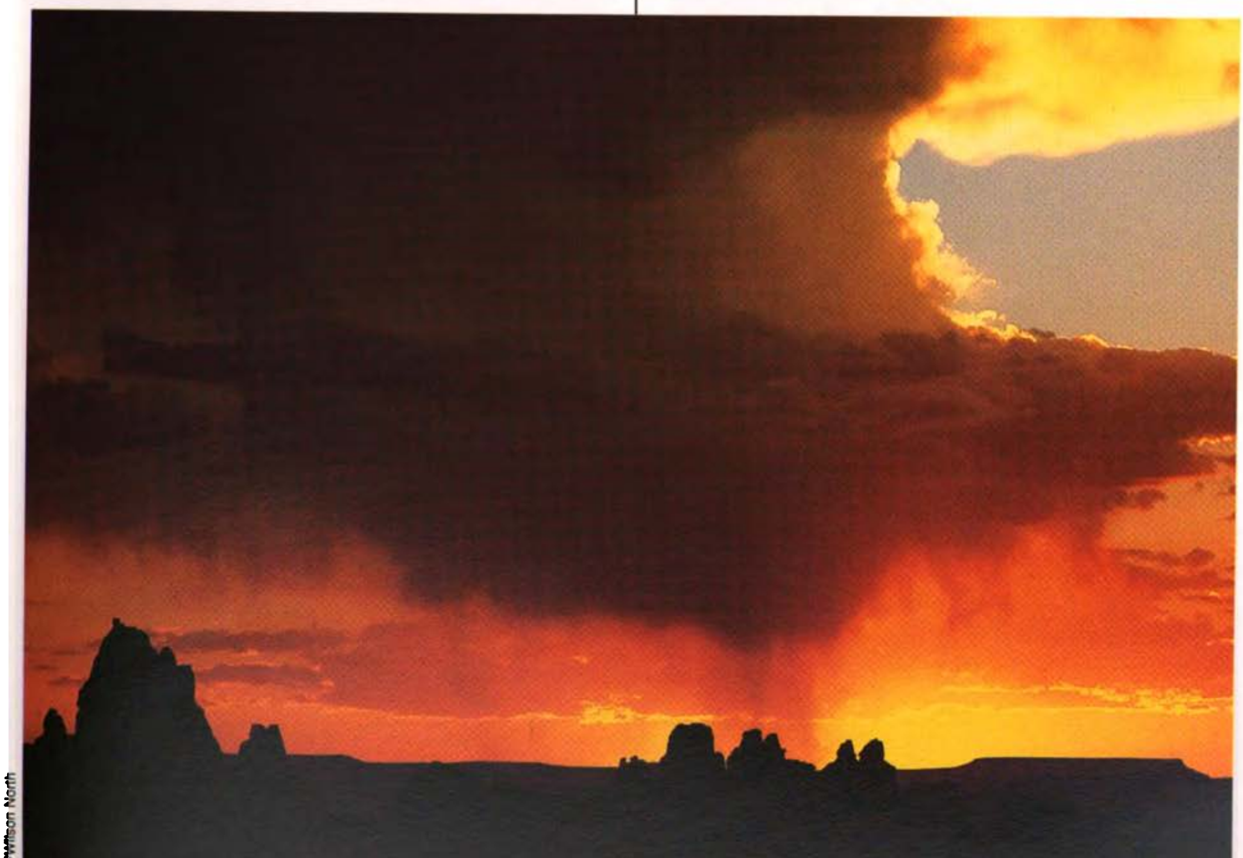

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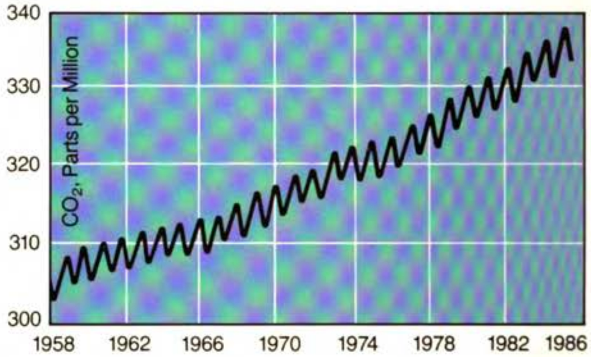
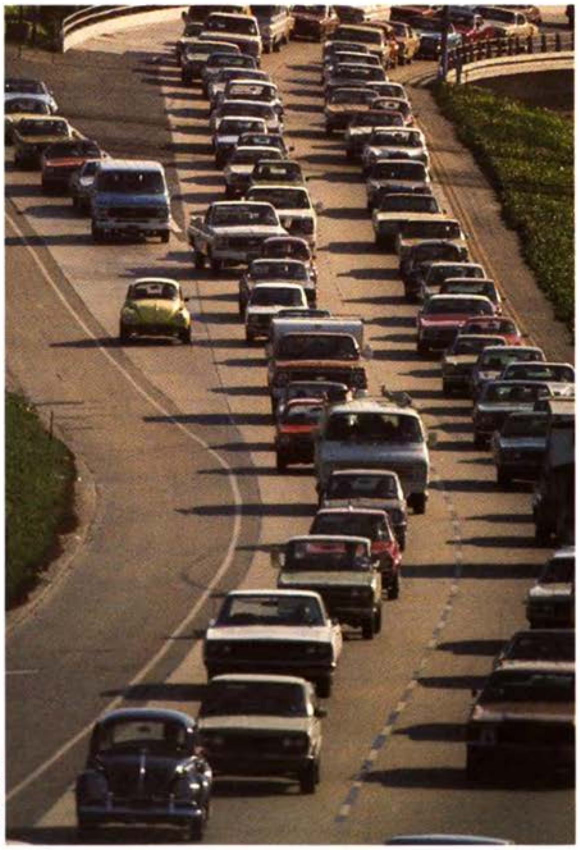
deforested land is planted to other vegetation, and since substantial afforestation may be occurring at northern midlatitudes, the net effect on carbon-dioxide balance remains unclear, but such changes are almost certain to alter the ecology of the land in a variety of ways. For example, the clearing of tropical forest, often by burning, is reducing the world's greatest reservoir of plant and animal diversity. In marginal agricultural areas, overcropping of the land and uncontrolled animal grazing may be turning productive soil into desert, a major source of dust that in turn can affect atmospheric properties and climate.

All of these human-induced changes are difficult to assess and measure accurately, but it is already evident that they are playing a role in shaping present and future global conditions. Now is the time to document these processes on a global scale and to identify the causal relationships among them, while there is still time to respond effectively.

Observed increase in atmospheric carbon dioxide, resulting in part from human activities.





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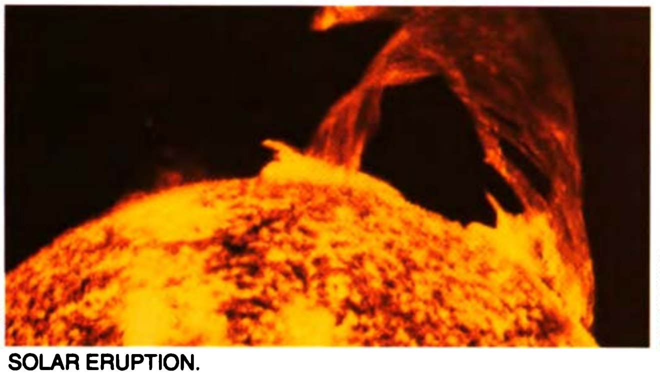

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SOLAR ERUPTION.

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The Earth and the Solar System

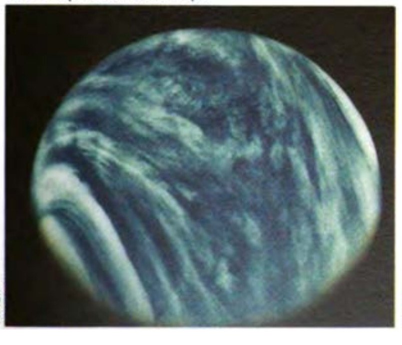
Any systematic approach to Earth studies must consider the Earth's membership in the Solar System — particularly the influence of the Sun and the coupling of the Earth to the space plasma of the heliosphere through its magnetosphere. As a matter of practical convention, the Earth System is here defined to lie within the mesopause of the atmosphere, 80-90 kilometers above the Earth's surface. Numerous measurements of properties of the Sun, magnetosphere, and outer atmosphere are nonetheless relevant to Earth System Science. The most important of these are the integrated flux of solar radiation arriving at the Earth, variations in the solar visible and ultraviolet spectrum, rates of ion transfer from the Earth's magnetosphere into the auroral zone below, and the modulation of both solar and Galactic cosmic-ray fluxes. A comprehensive strategy for such studies has recently been published by the Committee on Solar and Space Physics of the National Academy of Sciences' Space Science Board (Appendix A). The recommended program provides for the required measurements of solar luminosity and irradiance, particle generation, and magnetospheric precipitation, together with investigations of the basic plasma-physics mechanisms that control the variations in these quantities. Earth scientists will need to continue to work closely with the solar-physics and space-physics communities in support of the broad advances in these areas important to the context of Earth System Science.

Another area of importance to Earth science is the more general field of planetary science, especially studies of Mercury, Venus, Mars, and the satellites of Jupiter, Saturn, and Uranus carried out through NASA's program of Solar System exploration employing deep-space probes. This program continues to provide key insights into basic features of planetary structure and evolution, such as the formation and maintenance of planetary atmospheres. Strategies for Solar System exploration have been developed by the Space Science Board's Committee on Planetary and Lunar Exploration, and an implementation plan has recently been furnished by the NASA Advisory Council's Solar System Exploration Committee (Appendix A). While the Earth has been revealed as unique in many respects, this broad program of planetary science is, like solar and space-plasma physics, directly relevant to Earth System Science.

THE EARTH AND ITS VERY DIFFERENT NEIGHBORS.

Venus: How did its hot, "greenhouse" atmosphere develop?

Mars: Has liquid water ever flowed upon its surface?



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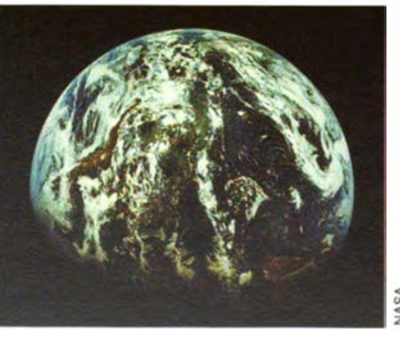

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Earth System Science

The study of the Earth is on the verge of a profound transformation. It has, until the present, advanced largely through the pursuit of specialized disciplines, such as geology or oceanography, each primarily concerned with an individual component of the Earth. Global connections among the Earth's components began to be recognized in the last century. Only recently, however, have we gained sufficient understanding of these connections to begin to study the Earth from a more unified point of view. In anticipation of deeper insights into the interactions among the Earth's components and the information pathways that describe them, we may now take a systems approach to Earth science that utilizes global observing techniques together with conceptual and numerical modeling.

The stage has thus been set for a new approach to Earth studies — Earth System Science — which builds upon the traditional disciplines but promises to provide a deeper understanding of the interactions that bind the Earth's components into a unified, dynamical system. Fundamental to this new approach is a view of the Earth System as a related set of interacting processes operating on a wide range of spatial and temporal scales, rather than as a collection of individual components. Figure 1 illustrates this view. The range of phenomena and processes involved extends over spatial scales from millimeters to the circumference of the Earth, and over timescales from seconds to billions of years.

Important interactions connect many of these processes and thus bridge widely separated spatial and temporal regions of Figure 1. Once change is introduced, it can propagate through the entire Earth System. Because of the interactions among the Earth's components, change in one component affects many others in both space and time. Volcanic activity, for example, occurs widely along intersections of the Earth's crustal plates and is driven by mantle convection on long timescales; yet the effects of eruptions are felt locally within hours or days and then, over larger areas, for months or years because of deposition of dust and gases in the atmosphere. It is the task of Earth System Science to continue to probe such interactions, to document their operation, and thus to provide a deeper understanding of the Earth System as a whole.

Our present knowledge of these interactions is, however, highly uneven. The convective processes responsible for changes in the solid Earth, although manifested in tectonic motion, earthquakes, and volcanic activity, are largely hidden from direct observation in the Earth's interior. While new technology for seismic observations is permitting more complete investigations of internal structure than ever before, our knowledge of solid-Earth characteristics and interactions remains less extensive than our knowledge of the fluid and biological Earth, which can be studied directly on the Earth's surface.

THE SOLID EARTH

Driven largely by internal energy sources, primarily radioactivity, the inexorable processes of solid-Earth change dominate all others on timescales of millions of years and longer. Some of the most important current investigations are the accurate determination of lithospheric plate motions, including continental deformation and evolution; the mapping of composition, structure, and convective patterns in the mantle; and the elucidation of the dynamo mechanism in the core that gives rise to the Earth's magnetic field and its reversals of polarity. Earth processes acting over millions to billions of years and their relationships to other processes operating on shorter timescales are depicted schematically in Figure 2a.

Plate Motions and Mantle Properties

Despite the recent triumphs of plate-tectonic theory, we need still better descriptions of the motions of the plates themselves. Within the past several years, Very Long Baseline Interferometry (VLBI) and satellite laser ranging techniques have begun to measure the rates of continental separation with convincing accuracy. These are in agreement with the average rates deduced from the geological record. Measurements of plate deformation are of high practical as well as scientific interest, since it is the accumulation of this deformation over timescales of decades that triggers earthquakes. In addition, we need further insights into the mechanisms responsible for the assembly and continued evolution of the Earth's continents, since these mechanisms remain poorly understood.

Plate motions arise from convective processes in the underlying mantle. It is only recently that satellite-based measurement systems have been able to record plate motions and accelerations with the precision that can lead to comprehensive understanding of mantle circulation. Additional recent insights into mantle properties and structure (e.g., the inhomogeneity of the mantle) have followed the application of tomography to seismic data, but the density of seismic observatories must be increased to realize the full potential of this technique. Understanding the nature of mantle convection and the origin of magmas and volcanoes requires observational, analytical, and experimental studies of these mantle properties.

In addition, precision altimetry from the Seasat spacecraft in 1978 demonstrated the great promise of space observations for the systematic mapping of mantle convective patterns: accurate measurements of sea-surface elevation produced a much improved determination of the oceanic geoid, which in turn led to the detection of mantle-circulation effects through their influence on the Earth's gravitational field. Global satellite observations of the geoid, particularly over the continents, are needed to provide data for numerical models of the mantle and to establish quantitative connections between mantle circulation and tectonic activity.

The Magnetic Field

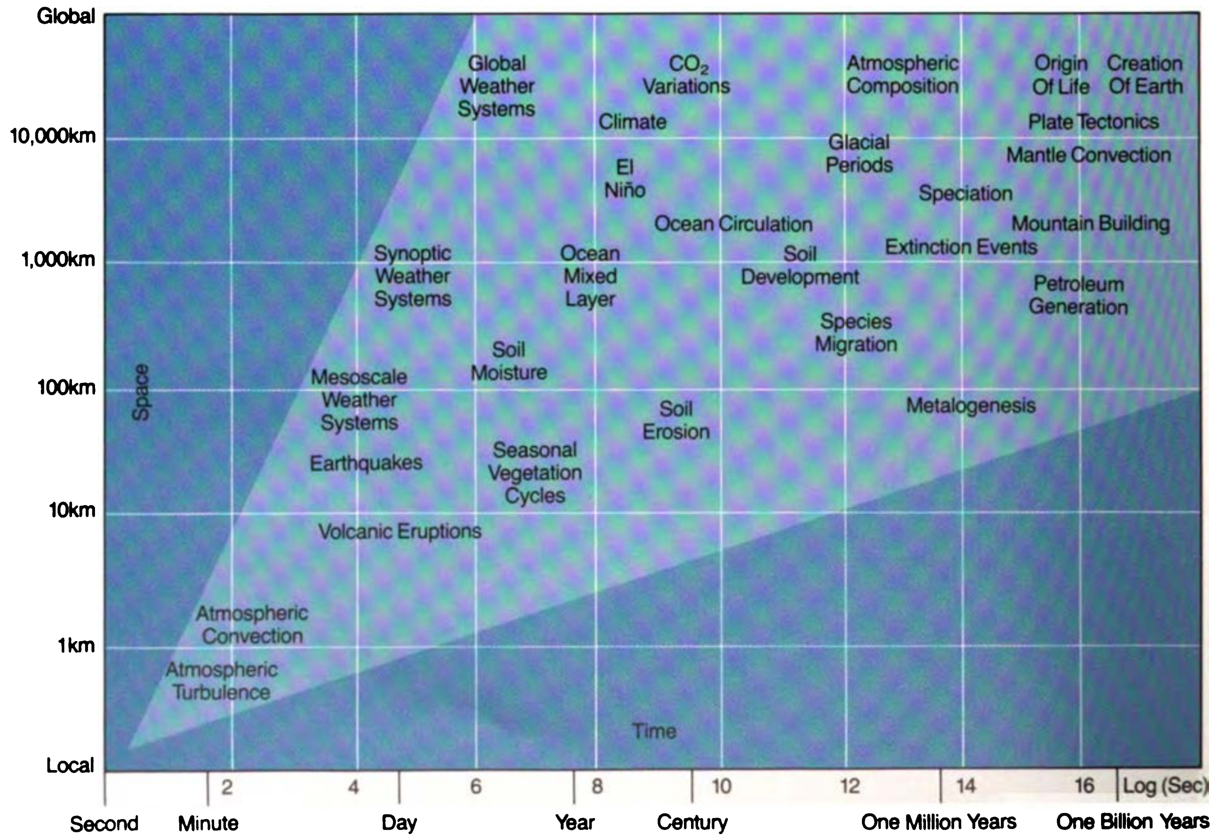
The thermal and compositional structure of the Earth's core, together with the dynamo mechanism responsible for the Earth's magnetic field, remain obscure in detail. We cannot predict the short-term changes in the geomagnetic field observed at the Earth's surface or explain why this field undergoes sporadic reversals of polarity a few times every million years. Studies of the Earth's magnetic field are important not only because of their role in elucidating core structure and in calibrating geological history, but also because they represent an outstanding opportunity to investigate a specific, accessible example of a pervasive, universal astrophysical phenomenon. Global satellite measurements are needed to separate that part of the Earth's field that arises from magnetized rocks near the Earth's surface from that part produced by electric currents flowing in the core and in the Earth's ionosphere and magnetosphere.

The Geological Record

While internal energy sources drive the evolution of the solid Earth, global surface features that can be observed from space reflect the continual contest between the constructive action of internal forces and the destructive effects of surface weathering and erosion. Surface geology is thus the library that holds the only long-term record of internal convective processes, as well as of other phenomena such as climate change, oceanographic variations, and biological influences.

The geological record has long been studied

Figure 1. EARTH SYSTEM PROCESSES: CHARACTERISTIC SPACE AND TIME SCALES



as a primary source of Earth history, and fossil remains have permitted the reconstruction of much of the course of life evolution. But research of the past several decades has demonstrated a more intimate connection between Earth evolution and the evolution of life upon it than was earlier suspected. For example, we now know that ocean biota of the past gave rise to the chemical reactions that led to formation of iron-ore deposits now on dry land. Moreover, the geological record reveals that the long-term evolution of the Earth has often been punctuated by episodes of catastrophic change that swept across the planet, affecting all components of the Earth System. New insights into global Earth evolution may be expected from continuing studies in continental geology.

THE FLUID AND BIOLOGICAL EARTH

By contrast with the solid Earth, changes in the fluid and biological Earth are highly sensitive to the Earth's external environment, being driven almost entirely by the energy of solar radiation. Diurnal and annual variations in insolation play a central role, and even subtle changes in the Earth's orbital parameters have important, long-term climatic effects. To the complexity of resulting motions in the atmosphere and the oceans must be added the extraordinary richness and variety of the biosphere, which has profoundly affected Earth evolution since the origin of life more than three billion years ago. Since most of these processes are open to direct observation, certain features of the fluid Earth, such as atmospheric circulation, are now becoming understood. Therefore, research attention is moving toward detailed study of less well understood components and the interactions among these components.

The study of past climate conditions—paleoclimate—is particularly important to our understanding of the more recent changes in the fluid and biological Earth and also to the testing of Earth System models. The data contained in sedimentary rocks, ocean sediments, and glacial ice are an invaluable resource for the probing of the complex interactions of the atmosphere, oceans, and marine and terrestrial biota. The information obtained so far is impressive but represents only a small fraction of that remaining to be discovered. Major programs of ice, ocean-floor, and continental drilling are necessary for further advances in paleoclimate study.

Studies of the past thirty years have permitted the development of a conceptual model of the fluid and biological Earth, shown schematically in Figure 2b (and in more detail in Figure 3), that describes global change on a timescale of decades to centuries. A notable feature is the presence of human activity as a major inducer of change; humanity must also live with the results of change from both anthropogenic and natural factors. The processes of global change on this timescale may be grouped into two basic classes: (1) the physical climate system, and (2) the biogeochemical cycles, woven together by the ubiquitous presence of global moisture in the forms of vapor, liquid water, and ice.

The Physical Climate System

The operation of the physical climate system is driven largely by the variation in solar heating with latitude, which produces differential patterns of circulation, precipitation, evaporation, surface conditions, vegetation, and thus climate. Most importantly, the latitudinal thermal imbalances produce a global circulation of the atmosphere, leading to great wind systems that are powerful engines for the global redistribution of heat, momentum, and material substances raised from the Earth's surface by convective currents. Passing over the oceans, these winds apply a stress to the upper ocean layer that helps to shape and drive global ocean current systems, as well as mixing this biologically productive surface region by means of waves. Winds and ocean currents are the Earth's global transport system for mass and energy; they tie the fluid and biological Earth together, producing both balance and change at the Earth's surface. All of these physical-climate processes, although studied for many decades, are incompletely understood on a global scale. However, satellite techniques offer a promising approach to obtaining the data needed for such an understanding.

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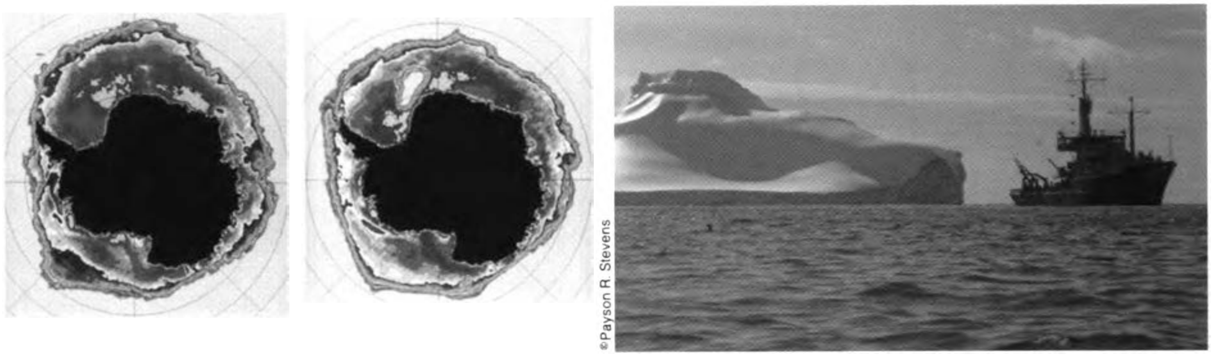
MODERN STROMATOLITES. These shallow-water constructions are produced by photosynthetic marine organisms that have helped shape the composition of the Earth's atmosphere by giving off oxygen.



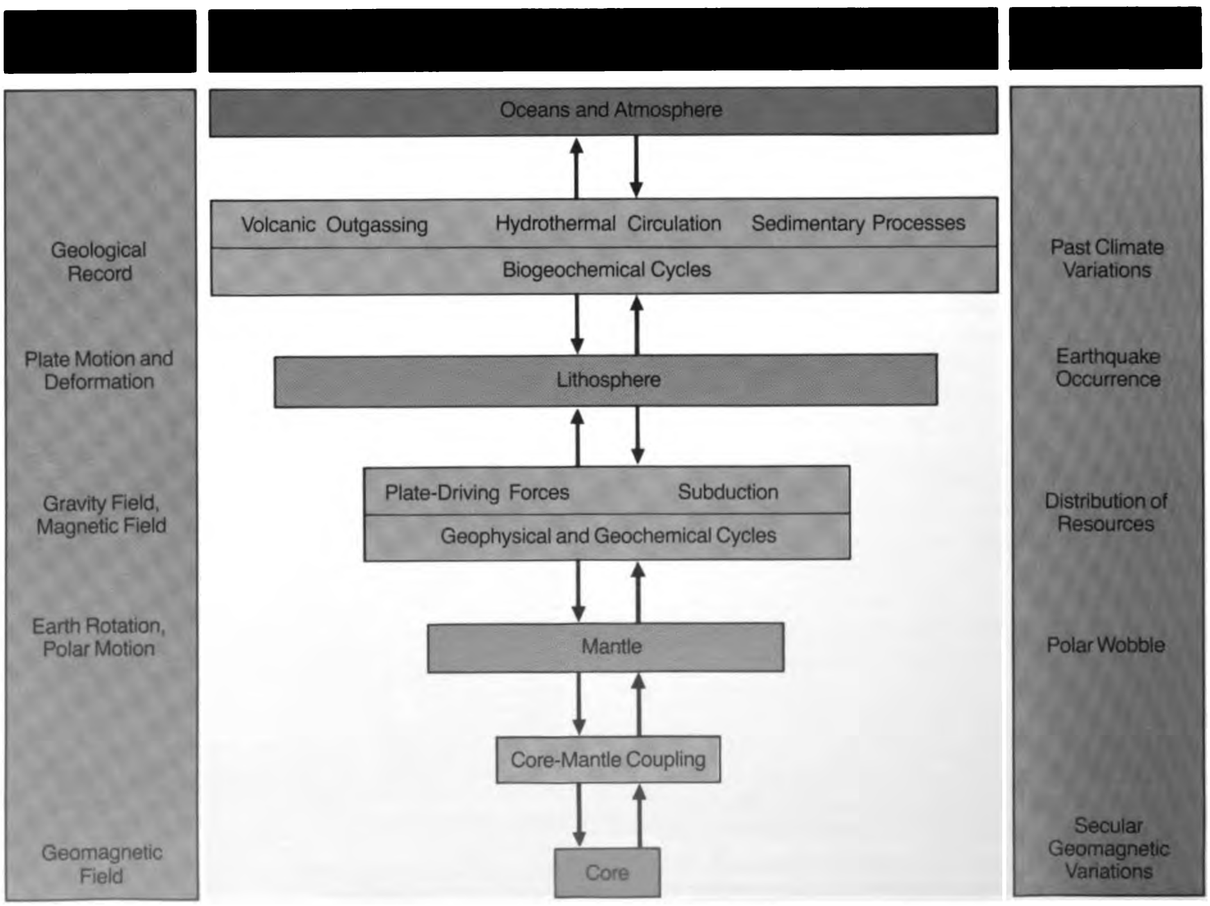
SATELLITE OBSERVATIONS OF ANTARCTIC SEA ICE COVER record interannual variations important to climate studies (far left, 1973, near left, 1976). Research vessels (right) provide *in situ* observations of related oceanographic features.

The Biogeochemical Cycles

The biogeochemical cycles — movements of key chemical constituents through the Earth System – are essential to the maintenance of life on our planet. Carbon, nitrogen, sulfur, and oxygen play primary roles, cycling in various forms through the atmosphere, hydrosphere, and lithosphere and interacting with other essential elements. Each cycle is marked by particular pathways and timescales, but they are all mingled and interrelated by biological processes. Although the role of local biology in the biogeochemical cycles has long been recognized, our understanding of these cycles is only now becoming sufficient to extend the analysis of biological sensitivities and influences to the global scale.

In addition to sustaining life, the biogeochemical cycles also play a role in determining the atmospheric concentration of the greenhouse gases that influence the Earth's energy budget. The most prominent of these, carbon dioxide, is of special interest because of the human role in perturbing the global carbon cycle through fossil-fuel burning. In addition, methane, nitrous oxide, and chlorofluoromethanes are

Figure 2a: SOLID EARTH PROCESSES



entering the atmosphere at accelerating rates; together with carbon dioxide, these gases are expected to cause important changes in global climate during the next century. They are emitted in the course of biological or human activity on land and in the oceans through processes that are still not well understood. Once released, the greenhouse gases circulate through the atmosphere and oceans until their ultimate destruction or deposition through a variety of chemical reactions. In the atmosphere, such reactions play a role in determining the extent of global air pollution and the chemistry of the Earth's protective ozone layer. In the oceans, some of these gases (or their oxidation products) are taken up by living organisms and thus eventually brought to the ocean floor within organic sediments. Although satellite observations of the atmosphere, oceans, and biosphere are essential for the study of the biogeochemical cycles, a program of *in situ* measurements of land and ocean biota, atmospheric chemistry and composition, and ocean sediments is also required.

Global Moisture

The existence of abundant water in all three phases is a primary difference between the Earth and the other planets in the Solar System, and is critical to the maintenance of life.

The global circulation of water in all forms plays a fundamental role in interactions of the Earth's surface with the atmosphere, particularly those governing the physical climate system and the biogeochemical cycles. The distribution of rainfall, snow, evaporation, and runoff affects the extent and distribution of biomass and biological productivity; changes in land cover and biological productivity can, in turn, affect hydrological processes on both local and global scales. Through evaporation, water exerts thermostatic control over local air temperature. Snow and ice cover help shape global climate and provide indicators of climate change. Water runoff couples the land with the oceans through the entrainment and transport of sediments and nutrients. Both liquid water and ice are powerful agents of erosion of land-surface features.

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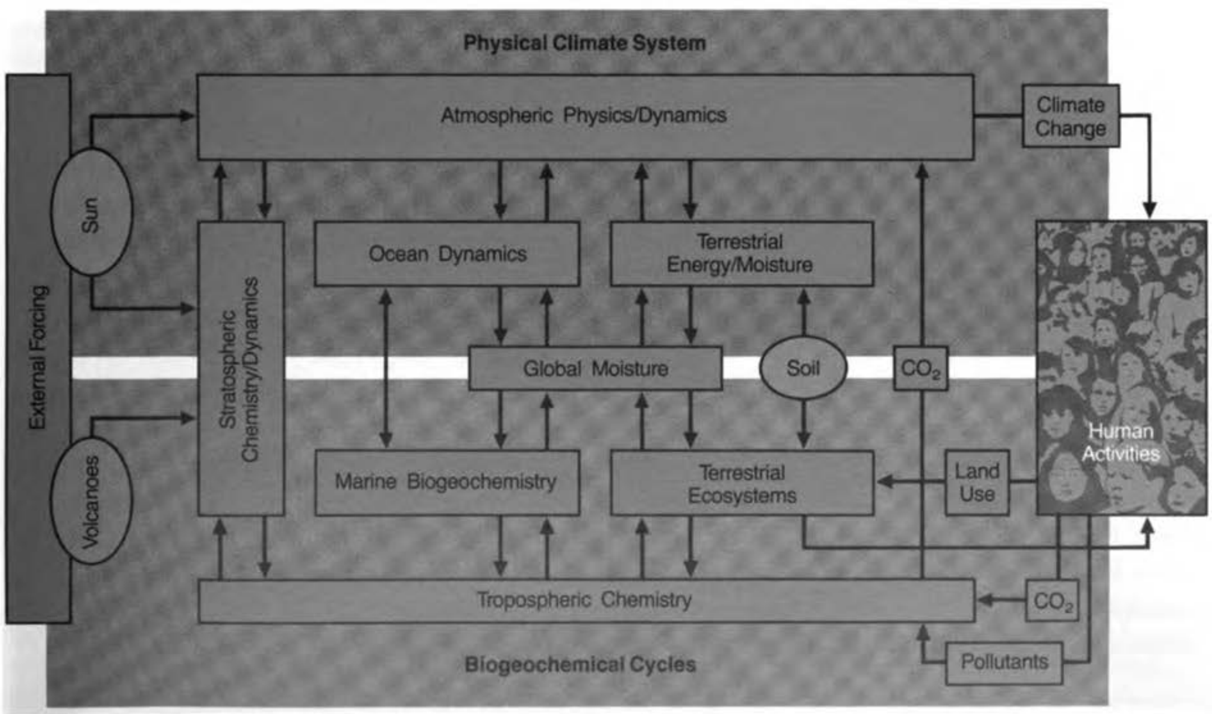
SAN ANDREAS FAULT traces slip zone between the North American and Pacific crustal plates.

Figure 2b: FLUID AND BIOLOGICAL EARTH PROCESSES



Despite the crucial importance of these processes for an understanding of global change and Earth evolution, the movement of moisture through the Earth System has not been adequately studied. For example, the extents of cloud, snow, and ice cover — major factors in the Earth's energy budget — are only now beginning to be documented in a manner that facilitates research analysis. We do not yet have data adequate for development of models of water circulation on a global scale; scattered point measurements are inadequate for descriptions of the complex interactions involved, although a combination of land measurements with remote-sensing observations of large areas has permitted quantitative study of some of the interactions. In many of the research areas relating to global moisture, such as precipitation and soil processes, we still lack some of the basic measurement concepts and techniques required for global, long-term observations. The measurement of global moisture must therefore be made a primary objective within studies of the fluid and biological Earth in the years ahead.

MODELING THE EARTH SYSTEM

The pervasiveness of change on our planet is abundantly documented in the geological record of continent and ocean distributions, in the climate cycles of ice ages and interglacial periods, and in the patterns of vegetation and species abundance. Over the time span of human history, such changes have been modest by comparison with those that have occurred over geological timescales. Within the next century or two, however, the effects of human activity may contribute to global changes comparable to those of geological history.

The reality of global change stimulates us to understand its causes and to determine the limits of the variability that arises through interactions among the components of the Earth System. To describe this multiplicity of interactions, we must transform our understanding of the functioning of the individual parts into quantitative models. These models can be used to simulate both the history and present state of the Earth System, and then to aid in predicting the future evolution of the system in response to selected changes in input variables.

A detailed conceptual model of the Earth System suitable for the analytic study of global change on a timescale of decades to centuries is presented in Figure 3. An implementation of this model does not presently exist, although individual modules describing some of the component pieces have been developed with

Atmosphere – Ocean Interaction

Coupled models of atmospheric and ocean circulation provide an example of our evolving ability to describe the interactions among Earth System components.

Advanced computer models of atmospheric circulation, based upon fundamental physical principles, have successfully simulated the major features of the climate and the statistics of short-term weather fluctuations. These atmospheric models treat a number of important input quantities as fixed, e.g., incident solar radiation, atmospheric composition (except for water vapor), land-surface topography, and such ocean properties as sea-surface temperature and sea-ice extent. Outputs from atmospheric models include the wind stress and net heat flux at the ocean surface, together with the balance of fresh-water evaporation and precipitation — the principal inputs to comparable models of ocean circulation (see Figure 3). Ocean models are not in such an advanced state of development as atmospheric models. They nevertheless produce useful estimates of sea-surface temperature and, in some versions, the extent and behavior of sea ice.

Atmospheric and ocean models are difficult to couple together because the characteristic response times of the atmosphere range from hours to days, whereas those of the ocean range from days or months to centuries. Despite these technical difficulties, promising simulations of the combined atmosphere-ocean system have now been run. Such coupled models permit the sea-surface temperature to be varied and thus allow, for example, an evaluation of the impact of clouds on atmospheric radiation. One important test of these models is provided by comparisons of model predictions with direct observations both of sea-surface temperature and of the fluxes of heat and fresh water at the atmosphere-ocean interface. Another significant test is furnished by the capacity of the coupled model to simulate phenomena that cannot be described by either model separately, such as the atmospheric fluctuation known as the Southern Oscillation, and El Niño, the associated temperature changes in the eastern tropical Pacific Ocean.

SCHEMATIC VIEW OF THE EARTH SYSTEM. Among the representative processes depicted are (clockwise from top); atmospheric chemistry (box); winds (blue arrows); evaporation and precipitation, critical ingredients of the physical climate system; ocean circulation (purple arrows) around polar ice cap; sea-floor spreading, reshaping Earth's surface and recycling elements through the interior (section); and photosynthesis by terrestrial vegetation, one of many contributors to the global carbon cycle.

considerable success. A few of these modules are currently being linked in a pairwise fashion as the next step toward assembling a complete interacting modular system.

The major components, shown as boxes in Figure 3, should be conceived of as groups of computer subroutines incorporating detailed knowledge of the relevant processes provided by the traditional Earth-science disciplines. The pathways (arrows) that connect these subsystems represent the information flow necessary to describe the interactions among them. The ovals and the attached arrows denote inputs from, or outputs to, an external environment. Inputs include possible changes in insolation or volcanic aerosols. Outputs include the deposition of plankton skeletons in deep-sea sediments characteristic of the distribution of sea-surface temperature. Human activity is here treated through scenarios — for example, through a conjectured, time-dependent input of atmospheric carbon dioxide from the burning of fossil fuels.

THE CENTRAL APPROACH AND THEMES OF EARTH SYSTEM SCIENCE

A fundamental aspect of Earth System Science, as illustrated by the discussion of Earth System models, is the emphasis on an integrated view of the interactions of the lithosphere, the physical climate system (including the atmosphere, oceans, and land surfaces), and the biosphere (coupled to the other components through the biogeochemical cycles). These systems participate individually and collectively in global change on all timescales. Once change is introduced, it can propagate through the Earth System. Because of the coupling among the Earth's components, change in one component can affect the others. Because of the nonlinearity of the system, change at one timescale can propagate into other temporal ranges.

Hence the central approach of Earth System Science is to divide the study of Earth processes by timescale, rather than by discipline. This approach incorporates specifically the interactions among the components, as required by an integrated and systemic view of the Earth. Accordingly, we must now view the Earth as a dynamical system, described by a collection of variables that specify its state and the associated rules for inferring how a given state will evolve. Through this central approach, we thus seek to (1) describe, (2) understand, (3) simulate, and (4) predict (perhaps in a statistical sense) the past and future evolution of the Earth on a planetary scale.

Describing Change: Global Observations

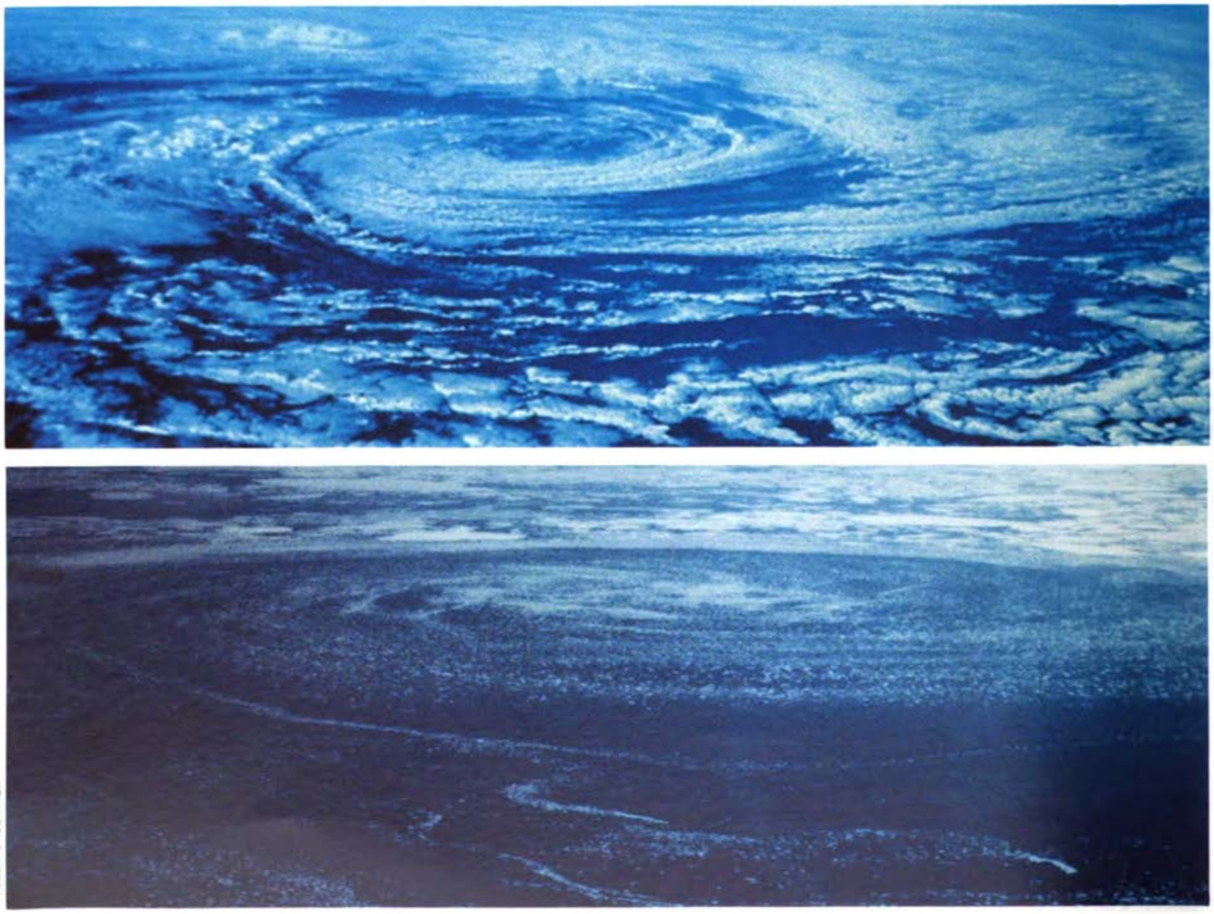
Change on a planetary scale can arise from three causes:

◆ External forcing, such as that provided by variations in the Earth's orbit around the Sun;

◆ Internal oscillations or instabilities, such as those inherent in the nonlinearity of the system or those introduced by biological evolution, volcanic eruptions, or continental rearrangement; and

◆ Perturbations generated by human activity.

Thus, to describe change on the planet—and hence to distinguish among the changes arising from external, internal, and human-induced effects—we must also carry out observations on a planetary scale. The present description of global change has been assembled from a variety of sources and observations over the past century or so. However, the global observations needed now to stimulate further progress in understanding the Earth System and its components can be obtained only from carefully designed space-based systems that provide the necessary simultan-



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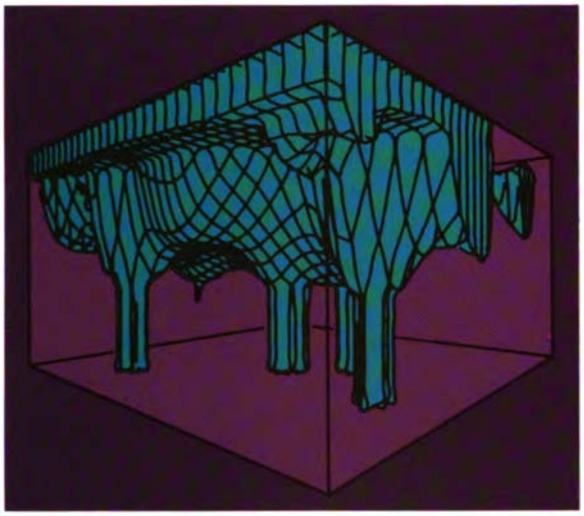
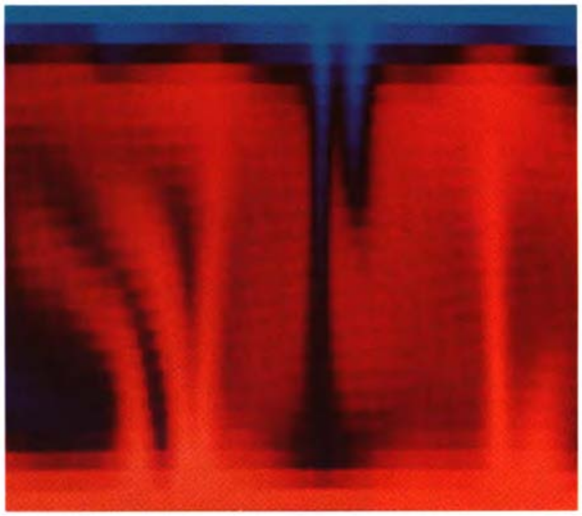
EDDIES ON ALL SPATIAL SCALES ARE CHARACTERISTIC OF THE FLUID EARTH. Clouds reveal eddy circulation in the atmosphere (top); sea ice marks eddy circulation in the ocean (bottom).



ADVANCED COMPUTER MODELS OF OCEAN EDDIES permit three-dimensional study of ocean circulation. Numerical simulations like these also provide guidance to future global observing programs.



COMPUTER SIMULATION OF CONVECTION IN THE EARTH'S MANTLE reveals hot upwelling (red) and cooler downwelling (blue). Mantle convection helps drive plate-tectonic motions.

eity and long-term continuity of global observations, supplemented by appropriate *in situ* measurements. At the same time, we must continue to improve our ability to construct a complete and reliable record of past global changes.

Understanding Change: Pattern to Process

To understand change on the planet requires that we establish plausible hypotheses of its causes, identify the physical, chemical, and biological processes involved, and ascertain the limits of its variability. The patterns observed from space, such as cloud cover and vegetation distribution, must be transformed into a quantitative understanding of the underlying Earth processes that control exchanges of energy, momentum, and chemical constituents. For some of the space observations, we can perform this transformation now; for others, basic research and *in situ* studies will be necessary before we can proceed. This knowledge must then be integrated into a conceptual framework that makes the observations meaningful.

Simulating Change: Earth System Models

To simulate change on the planet, we must use the information gained from the observational program to guide the development of conceptual and quantitative models of the Earth as a dynamical system that represent the diverse processes and their interactions. Such models will not only help to reveal the scientifically important questions, but will also provide vital guidance for the evolution of an increasingly effective observational program.

Modeling the Earth System requires that we go beyond the simplicity of traditional approaches, with the ultimate aim of modeling all Earth processes over all timescales. When a basic understanding of Earth System processes has been achieved, and modeling has advanced to the stage of quantitative simulations, we may then exploit the great range of conditions contained in the geological and paleoclimatological records to provide a variety of cases for verification studies. We also hope to determine whether the Earth System will achieve equilibrium, or rather will tend to oscillate between quasi-stable states, with dramatic episodes of global change accompanying the transitions between states.

Predicting Change: Decades to Centuries

To predict Earth evolution requires that we succeed in developing and verifying effective models of the Earth System. We propose to begin by emphasizing change on the timescale of decades to centuries. Adopting this tactic, we recognize that longer-term processes and structure provide the background environment, and that processes operating on shorter timescales contribute in statistical sum to the evolution of the Earth on human timescales. The resulting predictions will be of a statistical nature, revealing trends and ranges of values for such global variables as mean atmospheric temperature, atmospheric carbon-dioxide concentration, sea level, and the biomass on the land and in the ocean. Such predictions can also incorporate specified scenarios of industrial development, deforestation, and fertilizer use in order to gauge the effects of human activities — either as they are proceeding today, or as they might proceed if the world's peoples resolved to guide, rather than simply experience, the future of the planet.

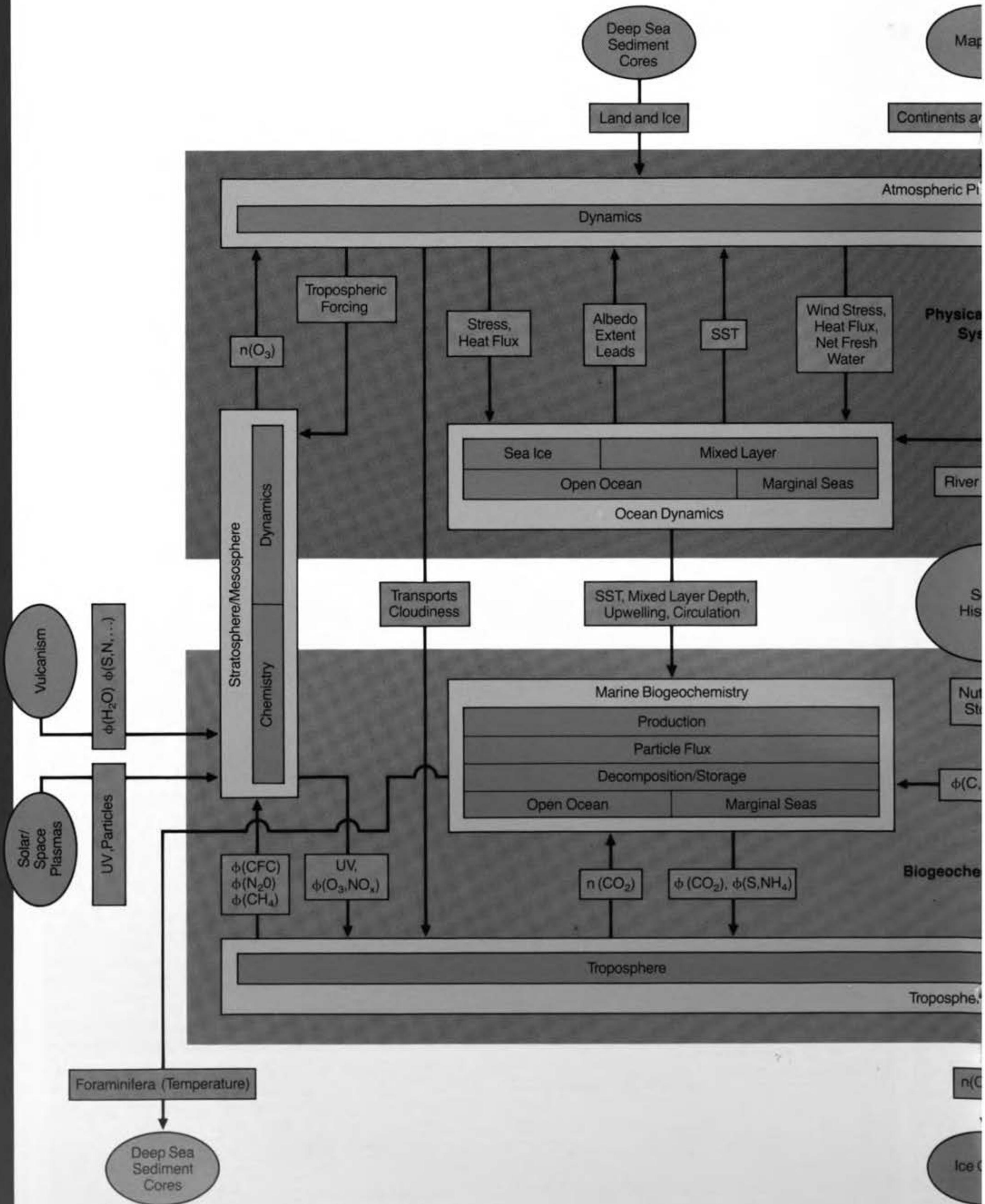
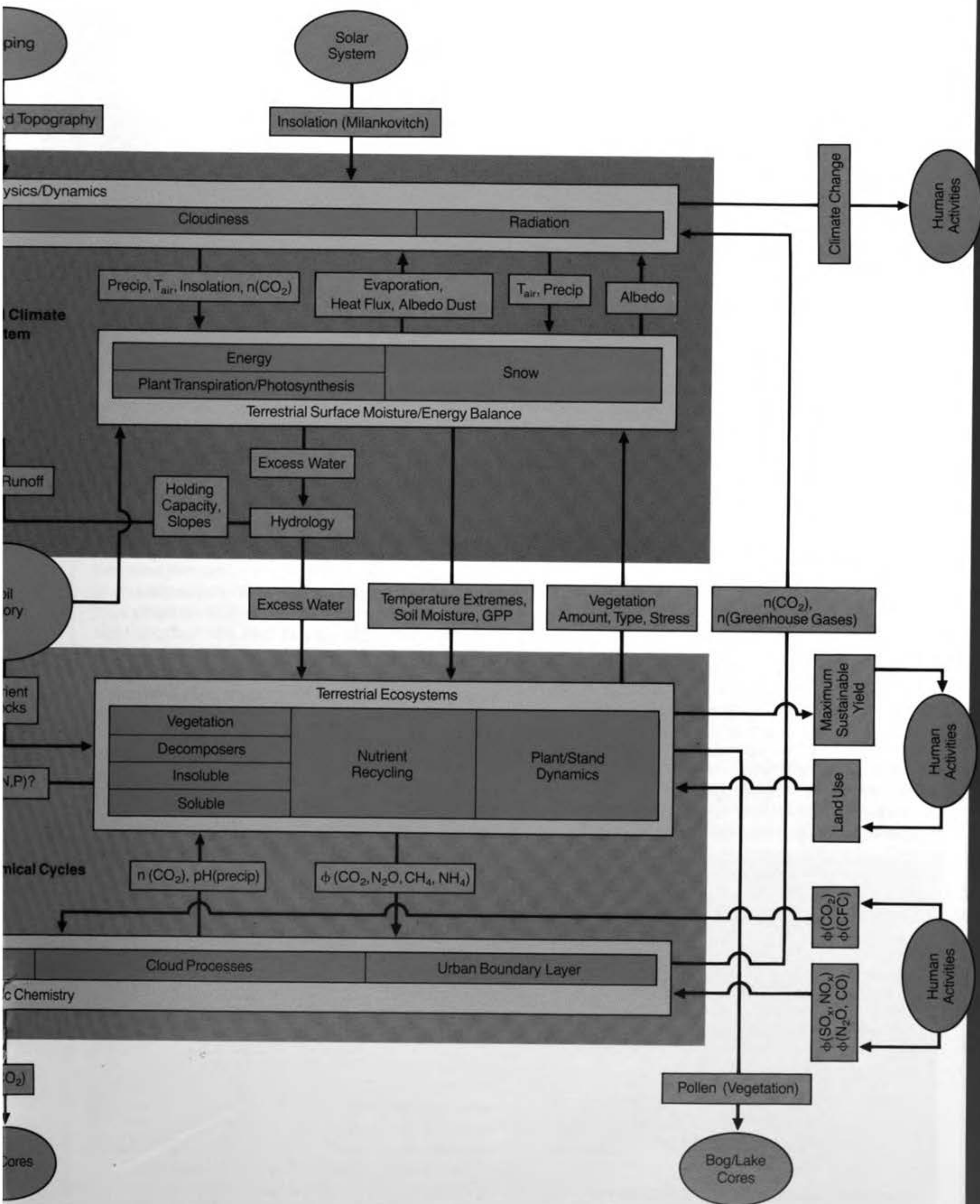
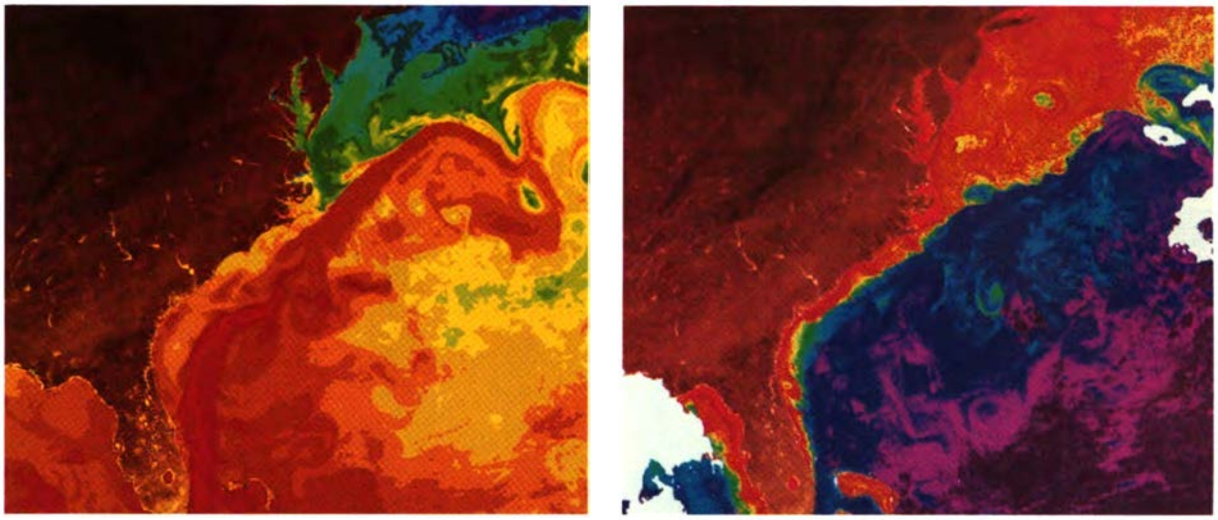


Figure 3. FLUID AND BIOLOGICAL EARTH PROCESSES: DETAILED INFORMATION FLOW
[$\phi(\ldots)$ = flux, $n(\ldots)$ = concentration]


Solar System
Insolation (Milankovitch)
Cloudiness
Radiation
Climate Change
Human Activities
Precip, T_{air}, Insolation, $n(CO_2)$
Evaporation, Heat Flux, Albedo Dust
T_{air}, Precip
Albedo
Energy
Plant Transpiration/Photosynthesis
Snow
Terrestrial Surface Moisture/Energy Balance
Excess Water
Holding Capacity, Slopes
Hydrology
Excess Water
Temperature Extremes, Soil Moisture, GPP
Vegetation Amount, Type, Stress
$n(CO_2)$, n(Greenhouse Gases)
Terrestrial Ecosystems
Vegetation
Decomposers
Insoluble
Soluble
Nutrient Recycling
Plant/Stand Dynamics
Maximum Sustainable Yield
Human Activities
Land Use
n (CO_2), pH(precip)
$\phi(CO_2, N_2O, CH_4, NH_4)$
$\phi(CO_2)$ $\phi(CFC)$
Cloud Processes
Urban Boundary Layer
$\phi(SO_x, NO_x)$ $\phi(N_2O, CO)$
Human Activities
Pollen (Vegetation)
Bog/Lake Cores



SATELLITE OBSERVATIONS OF SEA SURFACE TEMPERATURE (left) AND OCEAN COLOR (right) demonstrate correlation between marine productivity and physical oceanography. Simultaneous measurements from future satellite systems will expand our knowledge of such processes.

THE GOAL OF EARTH SYSTEM SCIENCE

We now need to gain a deeper understanding both of the components of the Earth System and the interactions among them. Our present knowledge of this system is, however, distinctly uneven and imbalanced. For example, we know much more about atmospheric dynamics than the workings of large-scale land ecosystems, and a great deal more about the coupling between the atmosphere and the oceans than about the coupling of the Earth's crust to the mantle below. Yet each of these represents an important component of the Earth System, and for none of them do we possess the knowledge needed to assess fully their roles in global Earth interactions. The study of the Earth System should therefore proceed across a broad front, in order to promote investigations of all the major Earth components while we are at the same time seeking new insights into the interactions among them. This study should be guided by the goal stated earlier:

> THE GOAL OF EARTH SYSTEM SCIENCE— To obtain a scientific understanding of the entire Earth System on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all timescales.

In addressing this goal, the Committee reached three important conclusions that must shape any strategy for Earth studies in the years ahead:

(1) Long-term, continuous global observations of the Earth are necessary for continued progress in Earth System Science. In particular, the intimate connections among the Earth's components cannot be fully revealed and documented without systematic measurements carried out over long timescales. Both space and *in situ* observations will be required to probe these connections.

(2) An advanced information system will be necessary to process and distribute the data from global observations. Such data embody not only the current state of the Earth but also, as time passes, its history, against which our understanding must be tested. An information system is also needed to facilitate data analysis, data interpretation, and quantitative modeling of Earth System processes by the scientific community.

(3) The development of conceptual and numerical models should proceed concurrently with the gathering of global observations and the establishment of an information system. These models of Earth System interactions should be both retrospective (designed to examine documented processes for causal relationships) and prospective (aimed at incorporating new knowledge into more refined models that yield more accurate forecasts of change).

THE CHALLENGE TO EARTH SYSTEM SCIENCE

The consequences of human activity in the processes of global change have introduced a new and compelling reason for additional research and for the pursuit of Earth System knowledge. Global changes induced by human activity are, moreover, difficult to distinguish from those arising from natural processes occurring on the same timescale of decades to centuries. We must thus recognize a new challenge to Earth System Science, one that provides a new research focus within the context of the more general goal stated earlier:

> THE CHALLENGE TO EARTH SYSTEM SCIENCE — To develop the capability to predict those changes that will occur in the next decade to century, both naturally and in response to human activity.

This challenge presents us with an unparalleled opportunity. Humankind is perturbing a responsive, dynamical system. By examining the Earth's response to that perturbation, we may be able to determine the fundamental physics, chemistry, and biology of the system itself.

ROLE OF SPACE OBSERVATIONS

Space observations are essential to the future study of the Earth as a system. Only space observations can provide the sheer volume of detailed, global synoptic data required to discriminate among worldwide processes operating on short timescales. In addition, advanced space platforms permit a variety of instruments to be placed at the same vantage point. Such a single vantage point greatly facilitates the integration of remote-sensing data and reduces decisively the problems of calibration, stability, and reproduceability that arise from attempts to interrelate measurements made from different sites at different times. Two decades of successful satellite observations have demonstrated that this is the most efficient way to deploy instruments for global study of the Earth from space.

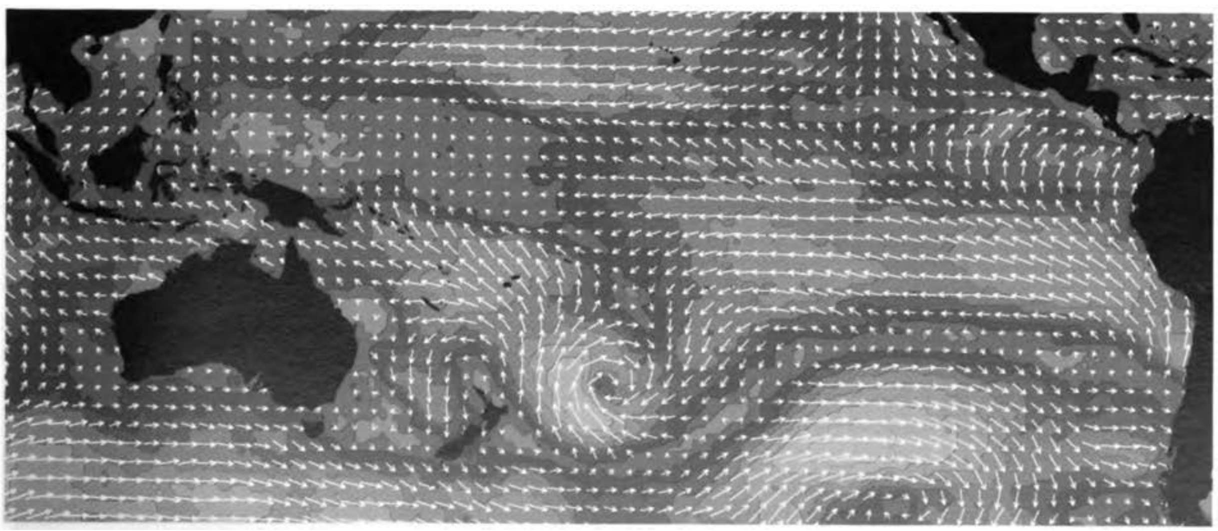
The unique role of space observations in Earth science has been recognized for more than a decade. In order to guide this area of research, the National Academy of Sciences' Space Science Board has provided an overall strategy for Earth science from space through a recent series of committee reports (Appendix A). Although these documents do not in general assign research priorities across all of Earth science, they do form a definitive compendium of research goals and measurement objectives for those programs conducted from space, on the basis of intrinsic scientific importance. The Earth System Sciences Committee has reviewed and accepted the Academy's recommendations, and has built upon them in developing an implementation strategy for Earth System Science.

The Committee also stresses that space observations are not, in themselves, sufficient to attain the goal of Earth System Science. For example, measurements made *in situ* are essential for subsurface sampling, for a variety of regional studies, and for the flexible, detailed investigation of individual localities. In addition, measurements *in situ* are necessary to validate satellite remote-sensing observations, so that, for example, the connections between the recorded radiation intensities and actual physical or biological properties may be established. Clearly, both measurements from space and measurements *in situ* will be needed to study the Earth as a system in the years ahead.

TWO PROGRAM PATHS

The Earth System Sciences Committee recommends that two program paths be followed during the next ten years to achieve our goals — one dealing with the solid Earth, and one dealing with the fluid and biological Earth:

(1) **Measurements of fundamental solid-Earth characteristics** are required for an understanding of planetary evolution on longer timescales. These include investigations of plate-tectonic



SATELLITE MAPS OF GLOBAL WIND PATTERNS, together with detailed *in situ* measurements, establish characteristics of the ocean-atmosphere interaction.

BALLOONS LIFT INSTRUMENTS INTO THE STRATOSPHERE to study the ozone layer important to the habitability of the Earth.

motions, continental deformation and evolution, mantle structure and circulation, and the generation of the magnetic field. Such studies are also relevant to processes operating on shorter timescales because of the dynamic couplings among the Earth's atmosphere, hydrosphere, crust, mantle, and core.

(2) **Studies of the fluid and biological Earth** are needed for an understanding of global change over the next decade to century. Such a program carries two essential implications:

◆ The primary emphasis is placed on the study of processes that are directly relevant to global change on a timescale of decades to centuries, such as the physical climate system, the biogeochemical cycles, and the measurement of global moisture. Valuable insights into the operation of these processes are to be found in the record of past climates and of the distribution of life over the Earth.

◆ A complementary emphasis is placed on the study of other processes that take place on longer or shorter timescales but that play a significant, indirect role in the processes referred to above. Examples include local weather patterns, sea-ice distributions, solar variations, cyclical changes in the Earth's orbital parameters, and solid-Earth evolution.

EXAMPLES OF REQUIRED MEASUREMENTS

The Committee has identified a comprehensive list of variables for which we must have long-term data sets in order to monitor the global state of the Earth. These variables, which will require measurements both from space and from the Earth's surface, may be placed into three classes:

(1) Variables now being measured by ongoing research and operational missions and programs, and whose measurement should continue. Examples include:

◆ The integrated energy output of the Sun in the direction of the Earth (solar constant);
◆ The vertical profile of atmospheric temperature, and atmospheric pressure at the surface;
◆ Cloud extent, sea-surface temperature, and ice and snow cover, documented in a manner that facilitates systematic research analysis;
◆ Concentrations of radiatively and chemically important gases, such as carbon dioxide and ozone;
◆ Motions and deformations of the lithospheric plates; and
◆ Index of vegetation cover.

(2) Variables not now being measured (or not being measured with adequate accurary or global coverage) but for which global measurement techniques exist and are ready for application. Examples include:

◆ Wind stress at the sea surface;
◆ Topography of the sea surface, for application to the study of ocean currents;
◆ Ocean chlorophyll concentration; and
◆ Earth's gravitational and magnetic field.

(3) Variables for which global measurement techniques remain to be developed and tested. Examples include:

◆ Global moisture content of the atmosphere, and precipitation;
◆ Components of the land-surface energy and moisture budgets;
◆ Biome extent and productivity; and
◆ Winds, especially in the tropics.

Tables 1 and 2, in the next section, present more extensive listings of representative missions, programs, and proposed measurements.

A FUTURE PROGRAM OF EARTH OBSERVATIONS

A strong consensus exists on the basic requirements for a future program of Earth observations. This consensus is reflected in a 1985 research briefing by the National Academy of Sciences to the Executive Office of the President (see below), which summarizes the steps we must take to implement a program of Earth System Science.

The Earth System Sciences Committee is in full agreement with these statements and describes its recommended program in detail in the next section. We concur with the need for a broadly based program emphasizing increased understanding both of the component parts of the Earth System and of the interactions among them. This effort will require significant attention to each of the components that appear in boxes in Figures 2b and 3. In this context, particular attention should be paid to nurturing studies of terrestrial ecosystems and marine biogeochemistry in order to strengthen our ability to treat quantitatively their roles in global change over the next decade to century.

ROCKET LAUNCHES SATELLITE FOR EARTH OBSERVATIONS. Earth System Science builds upon two decades of successful satellite programs.

Research Briefing by the National Academy of Sciences:

"To advance our understanding of the causes and effects of global change, we need new observations of the Earth. These measurements must be global and synoptic, they must be long-term, and different processes such as atmospheric winds, ocean currents, and biological productivity must be measured simultaneously. We have learned that major advances in Earth sciences have come from syntheses of new ideas drawn from such global synoptic observations. The synthesis of plate tectonics from large-scale data is a major step in understanding how the solid Earth works; the understanding of the dynamics of large-scale circulation of the atmosphere that comes from global observations has permitted a significant increase in the accuracy of weather predictions. Now we must take the next steps.

"Long-term continuity is also crucial. A 20-year time series of the crucial variables would provide a significant improvement in our understanding. Twenty years cover two sunspot cycles; it is the period over which we can expect the temperature change due to radiatively active gases to be larger than the natural system noise; it encompasses the eruptions of 5 to 10 volcanoes and the occurrence of 2 to 5 El Niños; and it is the period over which we can expect to see the major effects of deforestation. Finally, we note the need for simultaneity. If we are to make progress in understanding the Earth as a system it is essential that we make physical, chemical, and biological observations all at the same time since the physics, chemistry, and biology are all interrelated.

"Until the advent of satellites, we had no techniques that could satisfy the needs for long-term, global, synoptic measurement of different processes on the Earth. Now we are on the verge of establishing a global system of remote sensing instruments and Earth-based calibration and validation programs. Together, these space- and Earth-based measurements can provide the necessary data. With the concurrent development of numerical models that can run on supercomputers, we have the potential of achieving significant advances in understanding the state of the Earth, its changes, feedbacks, interactions, and global trends on timescales of years to centuries.*"

Research Briefings, 1985. Committee on Science, Engineering, and Public Policy (COSEPUP), National Academy of Sciences (National Academy Press, Washington, D.C., 1985).

The Recommended Program

In developing its recommended program, the Earth System Sciences Committee recognized two distinct research eras delineated by the U.S. Space Station development schedule: a current, near-term era, extending over the next decade, that will utilize present satellite capabilities, and a long-term era beginning in the mid-1990's that will draw upon the new capabilities provided by the Space Station. The Committee has also examined the roles of Federal agencies during both of these program periods and placed them in the context of an international effort directed at global Earth studies. Following a presentation of its own budget estimates of the costs of implementing the recommended program, the Committee offers some concluding remarks on Earth System Science.

PRIORITIES FOR AN IMPLEMENTATION STRATEGY

In determining priorities, the Committee first considered the intrinsic scientific importance of each potential research contribution, particularly its relevance to the Goal and the Challenge of Earth System Science. The relevant reports of the National Academy of Sciences' Space Science Board, such as that of the Committee on Earth Sciences, provided essential guidance for these science-related decisions. Other Academy studies, for example the International Geosphere-Biosphere study, also furnished a valuable scientific perspective.

The Committee next examined the feasibility of proposed program elements in the time periods of interest. The required measurement technology, scientific personnel, and institutional resources must be projected realistically and carry a reasonable assurance of availability. The nature and magnitude of some of the tasks has dictated a careful appraisal of the roles of the Federal agencies engaged in Earth-science studies. Because many of these tasks require satellite observations, the Committee has taken into account the future availability of space observatories. Consideration of the resources and opportunities to be provided by the Space Station program were therefore important to the Committee's conclusions.

Finally, the Committee had to face the constraints, both technical and fiscal, that must inevitably restrict the scope of any national research program, even one as important to our future as Earth System Science. From the perspective of its science strategy, the Committee considered programmatic opportunities to attain the objectives stated in the Academy reports, examining the relevance, readiness, degree of community support, and cost of proposed missions. The Committee has tried to strike a balance between program needs, on the one hand, and a realistic demand on agency resources and capabilities, on the other.

In the opinion of the Committee, the sequence, programmatic balance, and — given the high national importance of the Goal and Challenge — the schedule of the integrated program recommended here reflect all of these considerations.

The program elements recommended for inclusion in the current, near-term era of research (the next decade) are:

- Continuing and operational space observations;
- Specialized space research missions;
- Other observing opportunities;
- Basic research and *in situ* observations;
- An advanced information system; and
- Instrument development.

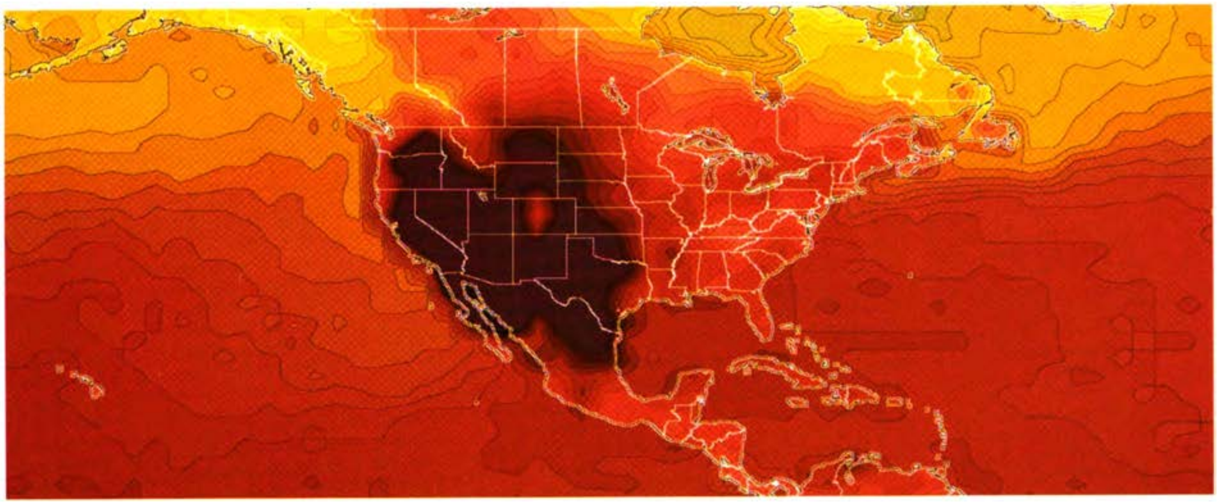
During the second era of research to follow (the mid-1990's and beyond), emphasis will shift to the integrated program of global measurements to be carried out by the proposed Earth Observing System (Eos), as well as NOAA's complement of operational instruments, both of which can utilize new space platforms in polar orbit provided by the Space Station program. These programs will be complemented by ongoing basic research and *in situ* observations, appropriate specialized space research missions, and observations from new space platforms in geosynchronous orbit.

THE CURRENT ERA

Continuing and Operational Space Observations

The United States civilian operating Earth-observing satellite systems, together with ground-based calibration and validation programs, furnish continuing global data on the atmosphere, oceans, solid Earth, and important solar and space-environment properties. From these sources, Federal agencies provide operational services critical to the protection of life and property, the national economy, energy development and distribution, and global food supplies.

At the same time, this ongoing measurement program, together with associated *in situ* investigations, provides a data base that is fundamental to research on the state of the Earth and global change. The Earth System Sciences Committee therefore concurs with the National Academy of Sciences' COSEPUP Panel on Remote Sensing of the Earth in emphasizing that present ongoing and operational satellite measurement systems must be continued —



NOAA OPERATIONAL SATELLITES MONITOR GLOBAL CHANGE. Mean daytime surface temperature, July 1979.

and improved as required — to provide accurate, homogeneous, and timely data. The Earth System Science program recommended here is based on the assumption that the operational system now in place will be continued.

NOAA is presently concluding contract negotiations for the next series of Geostationary Operational Environmental Satellite (GOES) spacecraft and payloads and has initiated a procurement through NASA for the continuation of the NOAA polar-orbiting spacecraft series. The GOES initiative will produce a series of Shuttle-launched, three-axis-stabilized spacecraft available for service beginning in 1990. These satellites, GOES-I through M, will offer direct-broadcast capabilities and simultaneous operation of imaging and sounding instruments. A greater number of spectral channels and higher resolution will also be provided. The extended polar-orbiting series, NOAA-K, L, and M, includes an Advanced Microwave Sounding Unit to provide improved soundings in cloud-covered areas and in the stratosphere, together with new information on sea ice, rain rates, and soil moisture. This series will remain in service until NOAA transfers its polar mission to the polar-orbiting platforms planned as part of the Space Station Complex.

Specialized Space Research Missions

Of particular importance in the near term is a carefully constructed sequence of specialized space research missions required for the study of specific Earth System properties and processes. Each is characterized by a choice of orbit and spacecraft design tailored to achieve the particular objectives of the mission. These missions must therefore be flown separately, and in a sequence that yields the optimum scientific return to the Earth System Science program as a whole. They are as follows:

◆ Earth Radiation Budget Experiment (ERBE). Because of its importance to climate studies, measurement of the Earth's radiation budget has been the objective of many satellite observations since the beginning of the space program. The ERBE program in progress, combining observations from a NASA research experiment (ERBS) in a low-inclination orbit with measurements from the operational NOAA-9 and NOAA-G satellites in polar orbit, is the first to provide these essential characteristics: adequate calibration, wide geographic sampling, broad spectral response, extensive measurements of the angular distribution of reflected and emitted radiation, unbiased diurnal sampling, and high spectral resolution. The projected ERBE observing period is 1985-1989.

◆ Upper Atmosphere Research Satellite (UARS). Scheduled for a 1989 launch, the approved UARS program is designed to improve understanding of the coupled chemistry and dynamics of the stratosphere and mesosphere, the role of solar radiation in these processes, and the susceptibility of the upper atmosphere to long-term changes in the concentration and distribution with altitude of key atmospheric constituents, particularly ozone. UARS data will be coordinated with results from the Solar Backscatter Ultraviolet (SBUV) spectrometer scheduled to be flown aboard operational meteorological satellites and the Space Shuttle during the UARS mission duration.

◆ Scatterometer (NSCAT) aboard the Navy Remote Ocean Sensing System (N-ROSS) satellite. The approved N-ROSS program, scheduled for launch in 1991, will carry four sensors: a scatterometer for ocean wind measurements, a microwave radiometer for measurements of sea-surface temperature, a microwave radiometer to monitor ice extent, and a radar altimeter to measure wave height and to locate oceanic fronts and eddies. NSCAT is planned to provide accurate, global wind-field data over a three-year period that will be of high importance to oceanography and meteorology. The instrument itself will satisfy both the research requirements of the scientific community and the operational requirements of the Navy. In addition to providing NSCAT to the Navy, NASA and NOAA plan to establish a ground data processing system to produce data products, including those of research quality, and to make them available to the oceanographic and meteorological communities.

◆ Ocean Topography Experiment (TOPEX/POSEIDON). This joint US/France mission, proposed as a 1987 NASA new start, will use radar altimetry to measure the surface topography of the oceans over a period of several years. When combined with appropriate *in situ* measurements, these observations will permit a determination of the three-dimensional structure of the world's ocean currents. The prime sensor will be a modification of the highly successful 1978 Seasat altimeter providing direct measurement of ocean topography through two-frequency operation. Highly accurate orbital characteristics are to be provided by receivers of the Global Positioning System; laser-tracking retroreflectors will be carried as well. Two experimental French instruments are part of the payload, and launch will be provided by Ariane. The TOPEX/POSEIDON satellite is scheduled to operate during the N-ROSS mission.

◆ Geopotential Research Mission (GRM). Candidate for a NASA new start in 1989, GRM is designed to measure spatial variations in the Earth's gravity and magnetic field over the entire globe to a resolution of 100 kilometers with unprecedented completeness and accuracy. The mission currently incorporates two low-drag spacecraft in co-planar, 160-km orbits, tracked by Doppler radar to an accuracy of one micrometer per second over their 300-km separation. GRM will yield important new insights into the Earth's remote interior. Measurements of the gravity field will elucidate the pattern and dynamics of thermal convection in the mantle, which drives plate-tectonic motions; observations of the magnetic field and its time variation will constrain models of the geodynamo in the fluid outer core of the Earth. Moreover, the timely flight of GRM is essential to a maximum utilization of data from TOPEX/POSEIDON by providing the geoid to which sea-surface heights are referred for studies of ocean circulation. The mission furthermore has important applications to additional studies of the thermosphere and mantle, and to geodesy.

All of the above missions are either operating, ready to proceed, or in advanced stages of development. Many of the measurements initiated by these missions should be continued as part of a program of long-term global observations from the mid-1990's onward.

Other Observing Opportunities

In addition to the specialized space research missions discussed above, there are opportunities to fly several other instruments, either on NOAA operational satellites, aboard the Space Shuttle, or on other spacecraft. All offer high scientific return at modest cost. Their development could be undertaken either by NASA, by NOAA, through a NASA-NOAA cooperative program, or through international collaboration.

◆ First among this set is an Ocean Color Imager. The Coastal Zone Color Scanner on the Nimbus 7 satellite, launched in 1978, has already provided a significant start on a long-term data set and has operated well beyond its design lifetime. This data set on biological activity in the world's oceans has a demonstrated utility to the research and ocean-user communities alike. This data stream must be continued with global oceanic coverage and improved flight hardware as soon as possible.

◆ The surface topography of the continents can be determined by a scanning radar altimeter flown on a series of Shuttle missions. This will furnish a data set of broad applicability in geology, geophysics and hydrology that can facilitate the interpretation of later high-resolution imagery.

◆ The chemistry of the troposphere is an area of growing emphasis in research and analysis as part of Earth System Science. The only trace chemical constituents of the troposphere currently measurable from space are carbon monoxide and water vapor. Carbon monoxide is indicative both of hydrocarbon oxidation and of the abundance of hydroxyl radicals which control the destruction of a number of other tropospheric gases. A version of the current Space Shuttle instrument, improved to detect carbon monoxide in three layers spanning the full height of the troposphere, would be a good candidate for flight on the NOAA morning satellites.

Basic Research and *In Situ* Observations

A program of basic research is needed to complement and make full utilization of the data from specific missions and projects recommended in this report. In particular, NASA, NOAA, and NSF will all need to expand considerably their basic Earth-science research efforts in order to strengthen ecological studies, fund new multidisciplinary research efforts in support of Earth System Science, and extend research in a

TABLE 1A

OBSERVATIONAL PROGRAMS FOR GLOBAL DATA ACQUISITION: REPRESENTATIVE EXAMPLES OF APPROVED AND CONTINUING PROGRAMS

Representative Space Programs

Program	Agency/Status	Objectives
POES: Polar-orbiting Operational Environmental Satellites (e.g., NOAA-7)	NOAA/ Operating	Weather observations
GOES: Geostationary Environmental Satellite System	NOAA/ Operating	Weather observations
DMSP: Defense Meteorological Satellite Program	U.S. Air Force/ Operating	Weather observations for Department of Defense
METEOSAT: Meteorology Satellite	ESA/Operating	Weather observations
GMS: Geostationary Meteorology Satellite	NASDA (Japan)/ Operating	Weather observations
METEOR-2: Meteorological Satellite-2	USSR/ Operating	Weather observations
LANDSAT: Land Remote Sensing Satellite	EOSAT/ Operating	Vegetation, crop, and land-use inventory
LAGEOS-1: Laser Geodynamics Satellite-1	NASA/ Operating	Geodynamics, gravity field
ERBE: Earth Radiation Budget Experiment	NASA-NOAA/ Operating	Earth's radiation losses and gains
GEOSAT: Geodesy Satellite	U.S. Navy/ Operating	Geodesy, shape of the geoid, ocean and atmospheric properties
GPS: Global Positioning System	U.S. Navy-NOAA-NASA-NSF-USGS/ Completion 1989	Geodesy, crustal deformation
SPOT-1: Système Probatoire d'Observation de la Terre-1	France/ Operating	Land use, Earth resources
IRS: Indian Remote Sensing Satellite	India/ Operating	Earth resources
Representative Space Shuttle instruments:		
ATMOS: Atmospheric Trace Molecules Observed by Spectroscopy	NASA/Current	Atmospheric chemical composition
ACR: Active Cavity Radiometer	NASA/Current	Solar energy output
SUSIM: Solar Ultraviolet Spectral Irradiance Monitor	NASA/Current	Ultraviolet solar observations
SIR: Shuttle Imaging Radar	NASA/ Current/In development	Land-surface observations
MAPS: Measurement of Air Pollution from Shuttle	NASA/ Current/In development	Tropospheric carbon monoxide
SISEX: Shuttle Imaging Spectrometer Experiment	NASA/Planned	Spectral observations of land surfaces
LIDAR: Light Detection and Ranging instrument	NASA/Planned	Surface topography, atmospheric properties

Program	Agency/Status	Objectives
MOS-1: Marine Observation Satellite-1	NASDA (Japan)/ Launch 1987	State of sea surface and atmosphere
LAGEOS-2: Laser Geodynamics Satellite-2	NASA-PSN (Italy)/ Launch 1988	Geodynamics, gravity field
SPOT-2: Système Probatoire d'Observation de la Terre-2	France/ Launch 1988	Earth remote sensing
UARS: Upper Atmosphere Research Satellite	NASA/ Launch 1989	Stratospheric chemistry, dynamics, energy balance
ERS-1: Earth Remote Sensing Satellite-1	ESA/Launch 1990	Imaging of oceans, ice fields, land areas
N-ROSS: Navy Remote Ocean Sensing System	U.S. Navy/ Launch 1991	Ocean topography, surface winds, ice extent
JERS-1: Japan Earth Remote Sensing Satellite-1	NASDA (Japan)/ Launch 1991	Earth resources

Representative International Programs for Measurements *In Situ*

Program	Organization/ Status	Objective
GEMS: Global Environment Monitoring System	UNEP/ Begun 1974	Monitoring of global environment
World Ozone Program	WMO-NASA-UNEP/ Operating	Atmospheric composition
Crustal Dynamics Project	NASA-23 nations/Begun 1979	Tectonic plate movement and deformation
Man and the Biosphere	UNESCO/ Operating	Ecological studies
International Biosphere Reserves	UN/Operating	Long-term ecological studies
ISCCP: International Satellite Cloud Climatology Project (World Climate Research Program)	WMO-ICSU/ Begun 1983	Measure interaction of clouds and radiation
ISLSCP: International Satellite Land Surface Climatology Project (World Climate Research Program)	WMO-ICSU/ Begun 1985	Measure interactions of land-surface processes with climate
TOGA: Tropical Ocean Global Atmosphere Program (World Climate Research Program)	WMO-ICSU/ Begun 1985	Variability of global interannual climate events
GRID: Global Resource Information Database	UNEP/ Begun 1985	Information on global resources

TABLE 1B

OBSERVATIONAL PROGRAMS FOR GLOBAL DATA ACQUISITION: REPRESENTATIVE EXAMPLES OF PROPOSED FUTURE PROGRAMS

Representative Space Programs

Program	Agency/ Status	Objectives
TOPEX/POSEIDON: Ocean Topography Experiment	NASA-CNES (France)/Start 1987, Launch 1991	Ocean surface topography
POES: Polar-orbiting Operational Environmental Satellite system — follow-on missions (NOAA K,L,M)	NOAA/ Planned	Advanced capabilities for weather observations
GOES: Geostationary Operational Environmental Satellite system — follow-on missions (e.g., GOES-Next)	NOAA/ Planned	Advanced capabilities for weather observations
RADARSAT — Canadian Radar Satellite	Canada/Start 1986, Launch 1991	Studies of arctic ice, ocean studies, Earth resources
MOS-2: Marine Observation Satellite-2	NASDA (Japan)/ Launch about 1990	Passive and active microwave sensing
GRM: Geopotential Research Mission	NASA/Start 1989, Launch 1992	Measure global geoid and magnetic field
Individual instruments for long-term global observations:		
OCI: Ocean Color Imager	NASA-NOAA/ Planned	Ocean biological productivity
ERB: Earth Radiation Budget instrument	NASA/ Planned	Earth radiation budget on synoptic and planetary scales
Carbon-Monoxide Monitor	NASA/ Planned	Monitor tropospheric carbon monoxide
Total Ozone Monitor	NASA/ Planned	Monitor global ozone
GLRS: Geodynamics Laser Ranging System	NASA/ Planned	Crustal deformations over specific tectonic areas
Laser Ranger	NASA/ Planned	Continental motions
Scanning radar altimeter	NASA/ Planned	Continental topography
Eos: Earth Observing System/Polar-Orbiting Platforms. NASA-NOAA program:	NASA-NOAA/ NASA Start 1989, Launch 1994	Long-term global Earth observations
NASA research payloads	NASA/ Planned	Surface imaging, sounding of lower atmosphere; measurements of surface character and structure; atmospheric measurements; Earth radiation budget; data collection and location of remote measurement devices
NOAA operational payloads	NOAA/ Planned	Weather observations and atmospheric composition; observations of ocean and ice surfaces; land surface imaging; Earth radiation budget; data collection and location of remote measurement devices; detection and location of emergency beacons; monitoring of space environment
European Polar-Orbiting Platform (Columbus)	ESA/Planned	Long-term comprehensive research, operational, and commercial Earth observations
Rainfall mission	NASA/Start 1991, Launch 1994	Tropical precipitation measurements
MFE: Magnetic Field Explorer	NASA/Start 1993, Launch 1996	Secular variability of Earth's magnetic field
MTE: Mesosphere-Thermosphere Explorer	NASA/Start 1995, Launch 1998	Chemistry and dynamics of upper atmosphere
GGM: Gravity Gradiometer Mission	NASA/Start 1997, Launch 2000	Gradient in Earth's gravitational field

Representative International Programs for Measurements *In Situ*

Program	Organization/ Status	Objectives
WOCE: World Ocean Circulation Experiment (World Climate Research Program)	WMO-ICSU-IOC-NSF-NASA-NOAA/ 1987 enhancement	Detailed understanding of ocean circulation
IGBP: International Geosphere-Biosphere Program (Global Change)	ICSU/ Proposed	Study of global change on timescale of decades to centuries
GOFS: Global Ocean Flux Study	NSF-NOAA-NASA/ Enhancement	Production and fate of biogenic materials in the global ocean.
GTCP: Global Tropospheric Chemistry Program	NSF-NASA-NOAA/ Enhancement	Tropospheric chemistry and its links to biota
Ocean Ridge Crest Processes	NSF-USGS-NOAA/ Enhancement	Chemistry and biology of deep-sea thermal vents, plate motions, crustal generation
Sensing of the Solid Earth	NSF-USGS-DoD-NASA/ Enhancement	Large-scale mantle convection, studies of continental lithosphere
Ecosystem Dynamics	NSF/ Enhancement	Studies of long-term ecosystems, biogeochemical cycles
Greenland Sea Project	ISCU/Planned	Atmosphere - sea ice - ocean dynamics

NASA SPACE RESEARCH MISSIONS PROBE GLOBAL EARTH PROCESSES. Joint U.S./France TOPEX/POSEIDON satellite will measure sea-surface topography to provide data for models of ocean circulation *(artist's conception)*.

number of present Earth-science disciplines, such as tropospheric chemistry.

NASA will require, for example, expanded capabilities to make measurements from non-space platforms, such as aircraft and surface stations, exploiting the latest technology. NOAA will need to improve the ground-based monitoring of sea levels and of long-lived atmospheric constituents from networks of stations and enhance its programs of modeling and research in the application of these data. With respect to spacecraft data, NOAA will need to increase its research on the application of operational satellite observations to Earth System Science problems. NOAA should also actively participate in national and international research projects designed to exploit operational satellite observations for Earth System Science applications, such as programs for cloud and land-surface climatology. Key NSF program enhancements include the establishment of terrestrial ecosystem observatories in which detailed *in situ* measurements of different biomes (vegetative groupings) can be made on a long-term basis for comparison with global satellite observations, together with studies of ocean circulation and related biogeochemistry. All three agencies will, in addition, need to support modeling and laboratory studies of Earth System components and their interactions. In shaping programs to attain these objectives, the agencies must furthermore take care to provide for the full participation of the university research community, which will play a pivotal role in the advance of Earth System Science.

Finally, the Committee wishes to stress the potential research importance of Earth System data to be provided by the commercial remote-sensing ventures now beginning operation. The Land Remote Sensing Commercialization Act of 1984 laid down extensive guidelines for the conduct of United States commercial operations; however, it is not yet clear how this act will actually be implemented in detail. The research community will, in particular, need access to commercial data for scientific purposes at a price commensurate with the resources of realistic research budgets. Moreover, the continuity and quality control of remote-sensing data are of the highest importance to research. These concerns must be met in any plan to transfer research instruments developed for remote sensing to commercial or Federal operational programs.

An Advanced Information System

Of paramount importance to the success of Earth System Science is an advanced information system that will promote productive use of global data. The worldwide space and *in situ* observations required for a deeper understanding of the Earth System can be utilized only if the research community has effective access to them. The design, development, and management of the requisite information system are tasks that approach, in scope and complexity, the design, development, and operation of space-based observing systems themselves. NASA, NOAA, and NSF will all benefit from such a system and should collaborate in this undertaking. Other interested agencies, such as the U.S. Geological Survey of the Department of the Interior, should participate as well.

The diversity of Earth-data sources mandates an information system of substantial capabilities in which flexibility of use is a key characteristic. There is, to begin with, a wealth of existing Earth System data, scattered among various locations, that could be rapidly applied to research problems if that information were more immediately accessible to the scientific community. Operational data currently processed and used by NOAA also need to be made available to the community through interactive access by remote terminals. In addition, data to be returned by specialized NASA space missions over the next two decades must be processed and distributed widely for scientific analysis. Finally, the information system will need to meet the data-handling requirements of the global system to observe the Earth envisioned for the mid-1990's and beyond. The system must thus permit scientists to obtain and combine data from all of these sources and to carry out detailed analysis of these integrated data on central and local computers. The system should also permit individual research groups to exchange analyses and to develop Earth System models interactively.

Among the more specialized requirements for an advanced information system are the following: the provision of data directories and catalogs, browse capabilities, and full documentation on sensors, missions, algorithms, and data sets; a hierarchical structure, so that active data bases of geophysical and biological properties can be maintained together with archives of more primitive sensor characteristics; the provision of utilities for higher-level data processing; and the linking of local work stations with observing-system control centers, so that qualified users can submit requests for specialized observations rapidly and directly. These features will, moreover, encourage the early formation of a community of interactive users of the system.

Such an information system is clearly a formidable undertaking, but it is essential to the pursuit of Earth System Science. The information system must be designed to accommodate the variety and complexity of the Earth itself, for it will provide our primary means for detecting and examining the processes of Earth evolution — particularly the processes of global change, arising from both natural and human causes, that are of such importance to the future habitability of the Earth. The contents of the information system, and the understanding that they generate, will constitute one of the chief legacies of Earth System Science to future generations.

Instrument Development

Finally, we need to begin, in the near term, a program of instrument development for spacecraft use that will ready a variety of experiments for service by the mid-1990's and beyond. Examples of such instruments are: (1) multichannel imaging spectrometers for study of physical, geochemical, and biological surface properties; (2) synthetic-aperture radars for ice studies, cartography, and surface properties; (3) high-resolution atmospheric sounders incorporating visible, infrared, submillimeter, and microwave channels; (4) laser ranging systems for geodetic measurements; (5) systems for high-precision ocean-floor measurements; (6) laser systems for measuring cloud heights, aerosols, temperature, moisture, chemical composition, and winds; and (7) improved microwave imagers for surface hydrologic studies and precipitation. Such instrument development is being proposed in anticipation of the requirements of the Earth Observing System (discussed below), and prototypes have in several cases already been scheduled for forthcoming Shuttle flights. The concurrent development of advanced instruments for measurements *in situ* will be needed to support and complement these space initiatives.

THE SPACE STATION ERA

Research in Earth System Science will change in two fundamental ways beginning in the mid-1990's. First, the near-term program described above will be underway: the flight of specialized space research missions can be expected to narrow the range of variables for further study, and other important elements of the near-term program should be in place. Second, we will have access to new technology, particularly a new generation of advanced observational platforms in space. These two developments will prepare the way for operation of the Earth Observing System.

Earth Observing System/Polar-Orbiting Platforms

By the mid-1990's, we will require a global observing system in space that utilizes highly capable polar-orbiting platforms and returns both research and operational data through the advanced information system described above. The Earth Observing System (Eos) presently under study by NASA, carried out in collaboration with NOAA's operational program, will incorporate both of these essential features. In combination with observations from geosynchronous platforms, several specialized space research missions, and complementary *in situ* measurements, Eos can provide the extended observations required for a fundamental understanding of the Earth System.

The planned instruments may be divided into three related classes: (1) a group of instruments that images the Earth's surface in the visible, infrared, and microwave regions and sounds the lower atmosphere; (2) a complement of radar instruments that will gather information on the character and structure of the surface; and (3) a group of instruments designed to study the composition and dynamics of the atmosphere and to measure the Earth's energy balance. Also proposed for Eos are a Geodynamics Laser Ranging System, for rapid measurements of crustal deformation over specific tectonic regions, and an Automated Data Collection and Location System to support automated *in situ* measurement devices.

The phased assembly of the Eos instrument complement has been discussed extensively within the Earth System Sciences Committee and its Working Groups. This scenario of instrument deployment has been found to meet the requirements of Earth System Science as they are anticipated to evolve in the mid-1990's and beyond, and to address the observational goals of the National Academy of Sciences' Research Briefing Panel of 1985 on Earth Remote Sensing:

> "To advance our understanding of the causes and effects of global change, we need new observations of the Earth. These measurements must be global and synoptic, they must be long-term, and different processes such as atmospheric winds, ocean currents, and biological productivity must be measured simultaneously . . ."

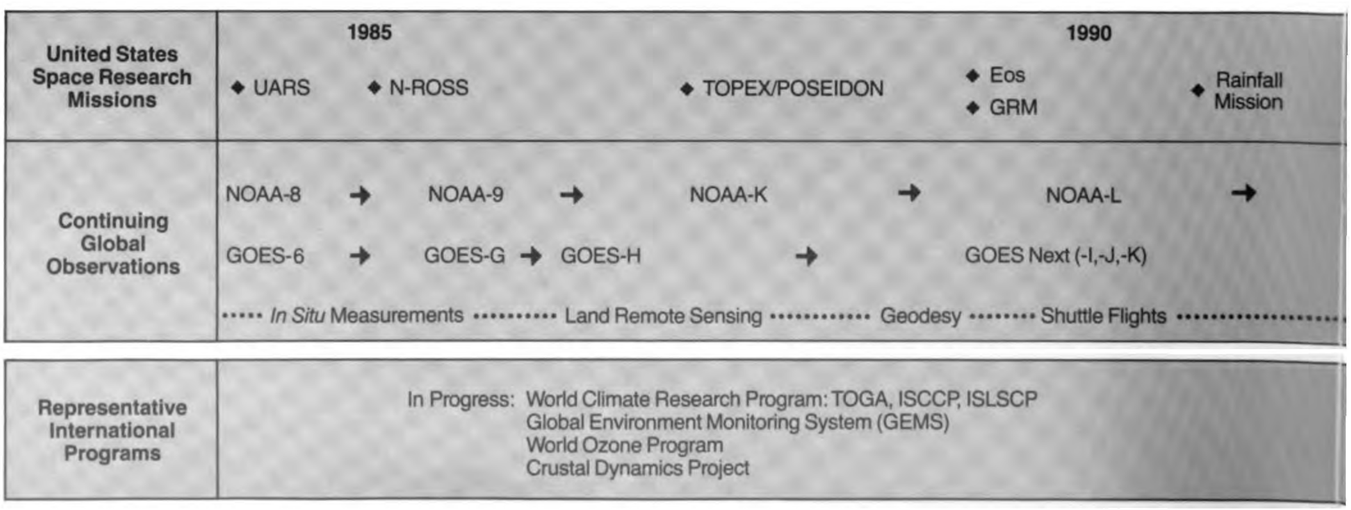
Accordingly, the Earth System Sciences Committee endorses the planned Earth Observing System as satisfying the requirements of ESSC and its Working Groups, and recommends an Eos new start in 1989.

As currently planned, NASA research instruments and NOAA operational instruments will jointly utilize polar-orbiting platforms of the Space Station Complex. Until the present, polar-orbiting satellites have been rather modest, automated devices devoted to a few instruments only, and inaccessible for servicing. The Space Station platforms of the mid-1990's are being designed with Earth System Science requirements in mind and would offer the following advantages:

◆ Expanded capability for instrument accommodation, power, and data telemetry. Because of the advent of advanced remote-sensing instruments and the need to integrate observations of different kinds, the NASA and NOAA payloads will make greater demands on platform services than can be met by platforms of current design.

◆ Accessibility for on-orbit servicing, payload augmentation, and instrument replacement by Space Shuttle crews. The periodic refurbishment and replacement of instruments should greatly increase the scientific return of Earth System Science payloads and facilitate the acquisition of long-term, self-consistent data

Figure 4. **EARTH SYSTEM SCIENCE THROUGH THE YEAR 2000** (◆ = New Start; ➔ = Continuing; ••••••• = Simultaneous and Ongoing).



sets. With the assurance of an extended operating lifetime, instruments may also be designed with more advanced features and capabilities than is feasible without serviceability.

The Committee furthermore notes that the Earth Observing System, NOAA operations, and the Space Station Complex are all being planned to include substantial international contributions and cooperation.

Geostationary Platforms

A second step toward a total system for global Earth observations will be provided by advanced platforms in geosynchronous orbit. These offer several fundamental advantages. First, high temporal resolution — limited only by instrument design and cost — can be brought to bear on the study of rapidly changing, global atmospheric phenomena. In the cases of land and ocean surveys, high temporal resolution helps to minimize data loss resulting from cloud cover and unfavorable atmospheric conditions. Geosynchronous orbit furthermore provides a fixed reference geometry for a given Earth location, facilitating data analysis and interpretation and the study of processes with significant diurnal variations.

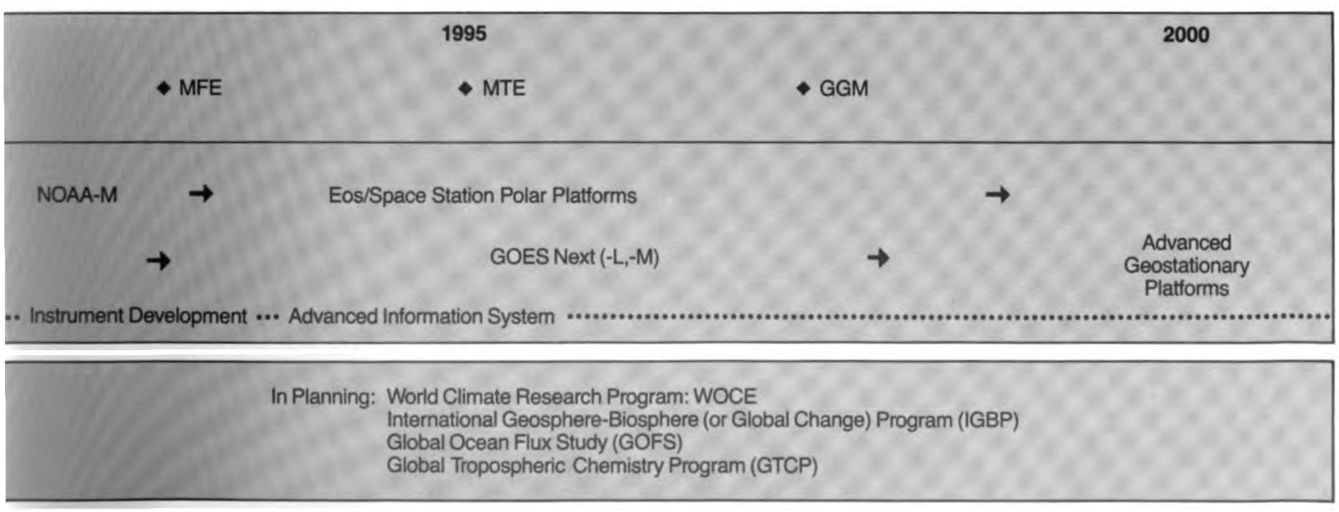
Operational geosynchronous satellites, in service since 1974, have carried imager/sounder instruments providing high-resolution visible and infrared images of the Earth. The infrared channels of the sounding instruments have provided temperature and moisture profiles over large areas of the Earth with high frequency. NOAA presently operates two GOES geostationary satellites and should continue to maintain and improve them. Future geosynchronous platforms with increased weight and power capabilities will permit advanced imager/sounder instruments operating in the visible, infrared and microwave spectral regions. The added capability of microwave sounding is not presently available because of the large antenna required for adequate spatial resolution at these high orbital altitudes, but such an advance is being studied as a possible addition to the next generation of NOAA geostationary satellites in the mid-1990's. In addition, a geostationary platform is currently under consideration as a growth element of the U.S. Space Station program. This platform may be expected to extend many of the capabilities and benefits of the Space Station polar platforms to geosynchronous orbit.

Specialized Research Missions

In addition to the specialized research missions recommended for implementation during the current decade and described earlier, several additional missions will be needed in the Space Station era to complement observations carried out by the Earth Observing System.

There is a critical requirement for space measurements of global precipitation. An exploratory mission is needed to test the feasibility of using active and passive microwave data, together with visible and infrared imagery, to derive useful estimates of rainfall amounts and distribution. A low-inclination orbit will permit study of the diurnal cycle of rainfall over the tropics and an assessment of the relationship of heat released into the atmosphere to anomalies in atmospheric circulation.

Also highly desirable in the Space Station era are: (1) a Magnetic Field Explorer (MFE) mission to derive an accurate description of the Earth's magnetic field and its secular variation at the measurement epoch; (2) a Mesosphere-Thermosphere Explorer (MTE) mission to address the chemistry and dynamics of the upper atmosphere, together with its links to the Sun above and the stratosphere below; and (3) a Gravity Gradiometer Mission (GGM) to measure the gradient in the Earth's gravitational field as a complement to the Geopotential Research Mission.



UNITED STATES AGENCY ROLES

Currently, NASA is responsible for general research and development in civilian satellite technology; NOAA is responsible for operational weather and ocean satellites and for development required to improve these capabilities; NSF is responsible for basic research in all areas of Earth science; and industry is beginning to play a role in land-surface measurements. The Earth System Sciences Committee does not at present see a need for major changes in these basic responsibilities, but it does see a need for more broadly defined roles for the agencies and for a much greater degree of coordination among them. A possible mechanism for fostering such coordination would be a high-level interagency group conducting in-depth program reviews and reaching agreement on priorities and implementation. An effective example of this approach is furnished by the Ocean Principals Group, which shapes policy for U.S. oceanographic research.

Role of NASA

NASA must continue its leadership in research from space relevant to Earth System Science. In particular:

◆ NASA should continue to have the primary responsibility for Earth-sciences research missions from space, including those of broad scientific scope, to study the Earth as an integrated system. NASA should continue to support and foster associated research, including advanced instrumentation development.

◆ NASA should continue to apply its capabilities in research and technology to the improvement of data transmission, archival, and retrieval techniques for utilization by the Earth-sciences community and by the NOAA operational program.

Role of NOAA

NOAA's role in the Earth sciences must be broadened beyond the present interpretation of its mission in order to meet national needs. The Earth System Sciences Committee urges a strengthening both of the operational satellite program and of the NOAA *in situ* research program on atmospheric and oceanic processes:

TABLE 2

REPRESENTATIVE EXAMPLES OF PROPOSED SATELLITE MEASUREMENTS*

Measurement	Implementation: Current Era	Implementation: Space Station Era
Solar energy output	ERBE, UARS	Eos
Ice extent, dynamics	DMSP, N-ROSS, ERS-1, JERS-1	Eos, DMSP, RADARSAT
Weather and climate: physical parameters	POES, GOES, DMSP, MOS-1, N-ROSS, ERS-1, JERS-1, (WWW)	POES, GOES, DMSP, MOS-2, Eos, RADARSAT, (WWW)
Stratospheric ozone chemistry & dynamics	UARS, POES	Eos
Tropospheric Chemistry	CO Monitor	Eos
Ocean surface winds & ocean currents	N-ROSS, TOPEX/POSEIDON, ERS-1, GRM, MOS-1, GEOSAT, (TOGA), (WOCE)	MOS-2, Eos, (TOGA), (WOCE)
Ocean spectral reflectivity, ocean productivity	OCI, (GOFS)	Eos
Precipitation, rainfall rates	Concept and technique development	Rainfall mission over tropics, Eos, GOES
Surface spectral reflectivity land-surface biology, continental geology	LANDSAT, Shuttle instruments, SPOT, (ISLSCP)	Eos, EOSAT, SPOT
Geopotential field & mantle circulation	GRM, (Global Digital Seismic Network)	(Global Digital Seismic Network)
Continental topography	Scanning radar altimeter	Eos
Magnetic field	GRM	MFE
Vegetation cover	LANDSAT, SPOT, JERS-1	Eos
Crustal deformation and plate tectonics	LAGEOS-1, LAGEOS-2, GPS, Laser Ranger, Shuttle instruments, (VLBI)	GLRS, Eos, GPS, LAGEOS-1, LAGEOS-2, (VLBI)
Land-surface energy and moisture budgets	Concept and technique development	Eos
Biome extent and productivity	Concept and technique development	Eos
Winds, especially in tropics	GOES, Concept and technique development	Eos

*Programs of complementary measurements *in situ* appear in parentheses; e.g., (WOCE).

◆ NOAA should provide the operational services, data-transmission network, and national archives, with an up-to-date interactive capability, for weather, climate, atmospheric chemistry, and oceanographic data in a manner that will support long-term scientific research requirements. Accordingly, NOAA should create formal mechanisms to involve the scientific community in determining and implementing requirements for NOAA's operational space and ground-based systems.

◆ NOAA should be assigned primary responsibility for conducting a program to obtain, maintain, and make accessible long-term (decadal) data bases that can be used to assess mankind's global impact or potential impact, from civil activities, on the oceans, atmosphere, and land.

◆ NOAA should conduct research in the atmosphere and oceans, especially applied research, including measurement and diagnostic modeling programs.

◆ NOAA should continue to have (as provided by the Land Remote Sensing Commercialization Act of 1984) primary responsibility for processing and archiving satellite data for land processes and for providing access to the data by the research community. NOAA should also continue its collaboration with the DoI/USGS in funding, defining, and maintaining an archive of land remote-sensing data for which DoI/USGS has the operational responsibility.

Collaboration Between NASA and NOAA

◆ NASA and NOAA should continue to investigate the feasibility and practicality of using the polar platforms of the Space Station to support both NASA research needs and NOAA operational needs. NOAA should provide typically 25 percent of the resources on any other operational satellite for support of research instruments and should give greater attention to the calibration and long-term stability of operational instruments in order to support research (as well as operational) needs.

◆ NASA and NOAA must collaborate in ensuring that satellite data on land processes acquired by NASA are transferred to NOAA as well.

Role of NSF

The role of NSF must be to continue to support studies in basic science and engineering that utilize all types of observations, both *in situ* and remote. The Committee believes it essential for NSF to view research utilizing satellite and complementary *in situ* validation and calibration data to be as appropriate for support by NSF as more conventional *in situ* process studies.

In addition, the Committee hopes that NSF will take an even broader role. Since future satellite programs will give us a new global view, but carry out only part of a given scientific investigation, the satellite missions yield maximum scientific return only if carried out in the context of large-scale field programs. Such programs are exemplified by the Global Atmospheric Research Program (GARP), funded jointly by NASA, NOAA, and NSF, which produced a major improvement in satellite coverage of global weather. Today we are seeing the development of global studies to understand the Southern Oscillation and its manifestation, El Niño (the Tropical Ocean Global Atmosphere Program); large-scale ocean circulation and mixing (the World Ocean Circulation Experiment); global fluxes and transport of material in the ocean; terrestrial ecology; the structure of the Earth's crust; the role of land and ice in paleoenvironmental reconstruction and in sea-level changes; and others. All of these will have satellite observations as one of the central elements, and, to be successful, all will require major enhancements by NSF as well as other agencies.

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MEASUREMENTS *IN SITU* ARE NECESSARY FOR SUBSURFACE SAMPLING, REGIONAL STUDIES, AND DETAILED INVESTIGATION OF INDIVIDUAL LOCALITIES. Oceanographers study chemical composition of antarctic waters.

NASA

CONTINUOUS, GLOBAL OBSERVATIONS OF THE EARTH WILL BE NEEDED FROM THE MID-1990'S AND BEYOND. The Earth Observing System will utilize polar platforms planned as part of the Space Station program to make simultaneous measurements with a variety of NASA and NOAA instruments (artist's conception).

Collaboration Among NASA, NOAA, and NSF

In addition to the roles and responsibilities discussed above, there are two areas in which NASA, NOAA, and NSF must all work closely together:

◆ NASA, NOAA, and NSF will need to establish and develop the advanced information system required by Earth System Science as a cooperative venture. In particular, they should institute an appropriate advisory body, representing the scientific community, to recommend a management structure and functional specifications for the information system, so that it will be certain to meet the needs of the research community. This action should be taken at once, so that the components of the information system may be completed, tested, and ready for use by the early 1990's at the latest.

◆ NASA, NOAA, and NSF must also cooperate in programs of basic research, particularly the development of new conceptual and numerical models of the Earth System. Such cooperation is necessary, for example, to take full advantage of the national supercomputer network now being established through NSF for the analysis and interpretation of spacecraft data returned through NASA and NOAA programs.

Other Agencies

As pointed out by a recent report of the Office of Science and Technology Policy of the Executive Office of the President (see Appendix A), there are many Federal agencies that conduct or utilize space-related Earth-sciences research programs. In addition to NASA, NOAA, and NSF, principal participants include the Department of Interior (DoI), particularly the U.S. Geological Survey (USGS), and the Departments of Agriculture (USDA), Energy (DoE), and Defense (DoD). The Agency for International Development (AID), the Environmental Protection Agency (EPA), the Federal Emergency Management Agency (FEMA), and the Departments of Housing and Urban Development, Justice, and Transportation are also users of research data or results in one form or another. All of these agencies should be invited to collaborate, where appropriate, in the projects for which

NASA, NOAA, and NSF hold primary responsibility. Because of the international character of Earth-science research, the Department of State can be involved as well in assisting research programs.

INTERNATIONAL COOPERATION

International cooperation is essential to the global study of the Earth and to the success of the Earth System Science initiative proposed here, for two reasons. First, detailed global observations from space and from a variety of locations on the Earth's surface are required; the nations concerned must be included in the planning and execution of observational programs that affect them. In addition, other nations are planning major space systems for remote sensing of the Earth, which will provide significant data relevant to Earth System research.

International collaboration proceeds at three levels, all of which must be carefully coordinated. First, there is the traditional communication of scientists among themselves concerning scientific problems and the strategies for addressing them. This process is promoted at the international level (e.g., the International Lithosphere Program) primarily by the International Council of Scientific Unions (ICSU), as well as by a number of other organizations. Secondly, for any activity requiring systematic exchange of data or for access to the territory, airspace, or economic zones of other nations for Earth-science observations, there must be specific international arrangements. These are facilitated by an endorsement of such scientific activities by an established international agency or other appropriate body. International action to address the issues of physical climate change has already begun, but arrangements for study of the biogeochemical cycles have not yet been initiated.

Finally, the program will benefit from the increasingly explicit collaboration between governments in the instrumentation and operation of spacecraft. Bilateral agreements between space agencies are a proven mechanism for such collaboration. The European Space Agency (ESA) and NASA cooperated on early Space Shuttle scientific missions, and the number of collaborating nations is now increasing. For example, the TOPEX/POSEIDON oceanographic satellite is to be a joint mission of the U.S.A. and France; Canada, France, and the United Kingdom provide portions of the NOAA operational payload; and the LAGEOS-2 satellite will be launched in 1988 through a joint U.S./Italy program.

Coordination among U.S. and foreign agencies planning remote-sensing satellites for the near term is already well developed, implemented through such groups as the Committee on Earth Observations Satellites (CEOS). This coordination seeks to assure compatibility and international availability of data sets from the various systems. For the longer term, discussions among Canadian, European, Japanese and U.S. government remote-sensing specialists have revealed substantial commonality of measurement objectives for Earth observation from polar platforms of the Space Station. These discussions are expected to result in significant collaboration both in instrument development and in exchange and analyses of data.

A number of major international research programs relevant to Earth System Science, which involve (or should involve) U.S. participation, are now in place. The World Climate Research Program sponsored by ICSU and the World Meteorological Organization includes the following programs fundamental to ESSC goals:

◆ The Tropical Ocean Global Atmosphere (TOGA) program, recently instituted to determine the causes and establish the predictability of El Niño and Southern Oscillation events.

◆ The International Satellite Cloud Climatology Project (ISCCP), recently established to provide a global data set on the interactions of clouds and radiation, with applications to climate models.

◆ The International Satellite Land Surface Climatology Project (ISLSCP), recently begun to measure the interactions of land-surface processes with climate in specific biomes.

◆ The World Ocean Circulation Experiment (WOCE), now being organized within the World Climate Research Program to permit development of improved models of global ocean circulation on timescales of decades and longer.

Other programs important to ESSC goals include the following:

◆ The International Geosphere-Biosphere (or Global Change) Program (IGBP), now being formulated within ICSU to lead a worldwide study of global change.

◆ The Crustal Dynamics Project, begun in 1979 and involving NASA and bilateral agreements with 23 countries, designed to measure global plate tectonic movements.

◆ The International Working Group on Magnetic Field Satellites, recently formed to define and integrate measurements of the secular variation of the Earth's magnetic field.

◆ The Global Ocean Flux Study (GOFS), proposed to extend our understanding of processes responsible for production and fate of biogenic materials in the sea from regional to ocean-basin and global scales.

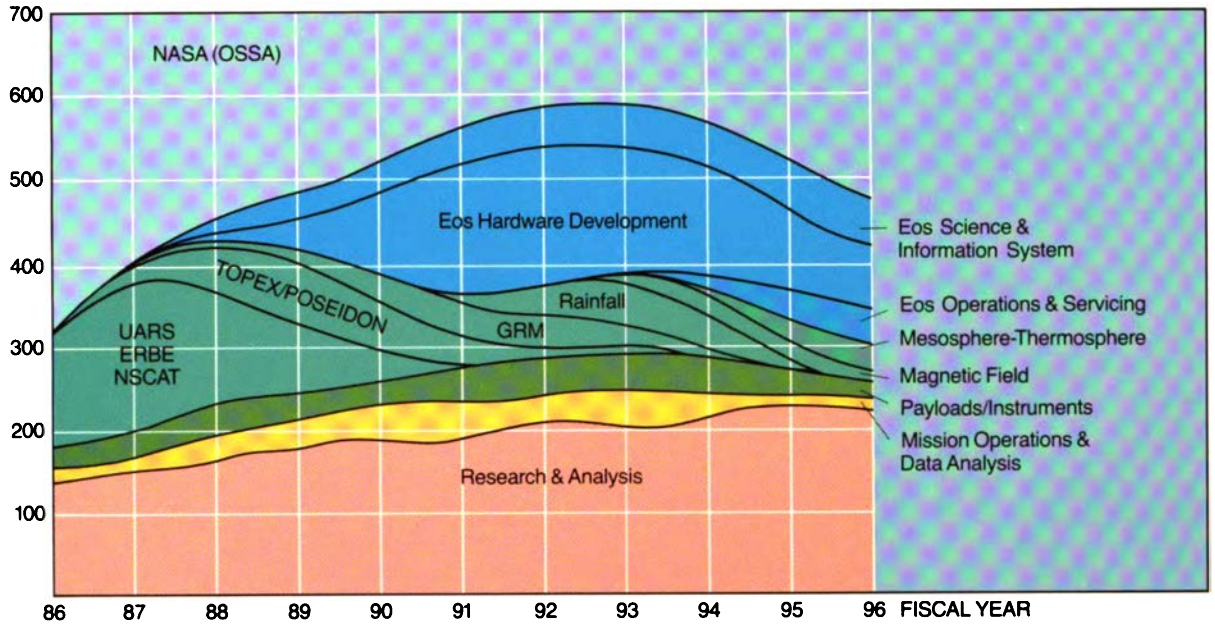

Figure 5. ESSC ESTIMATE OF NASA BUDGET (FY 1986 dollars, in millions).

BUDGET ESTIMATES

The schedule of the Earth System Science program recommended by the Committee is presented in Figure 4. In Figures 5-7, we present our estimates of the National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), and National Oceanic and Atmospheric Administration (NOAA) budgets required to implement our recommendations. These estimates are stated in current dollars and do not include inflation.

The NASA budget reflects what we believe to be a reasonable allocation of the overall Office of Space Science and Applications (OSSA) budget to the scientific study of our planet.

The NSF estimate reflects a new emphasis on global geoscience following increased research interest in the opportunities inherent in a collaborative program in Earth System Science.

The NOAA budget estimates reflect an expanded level of service, but at a funding level

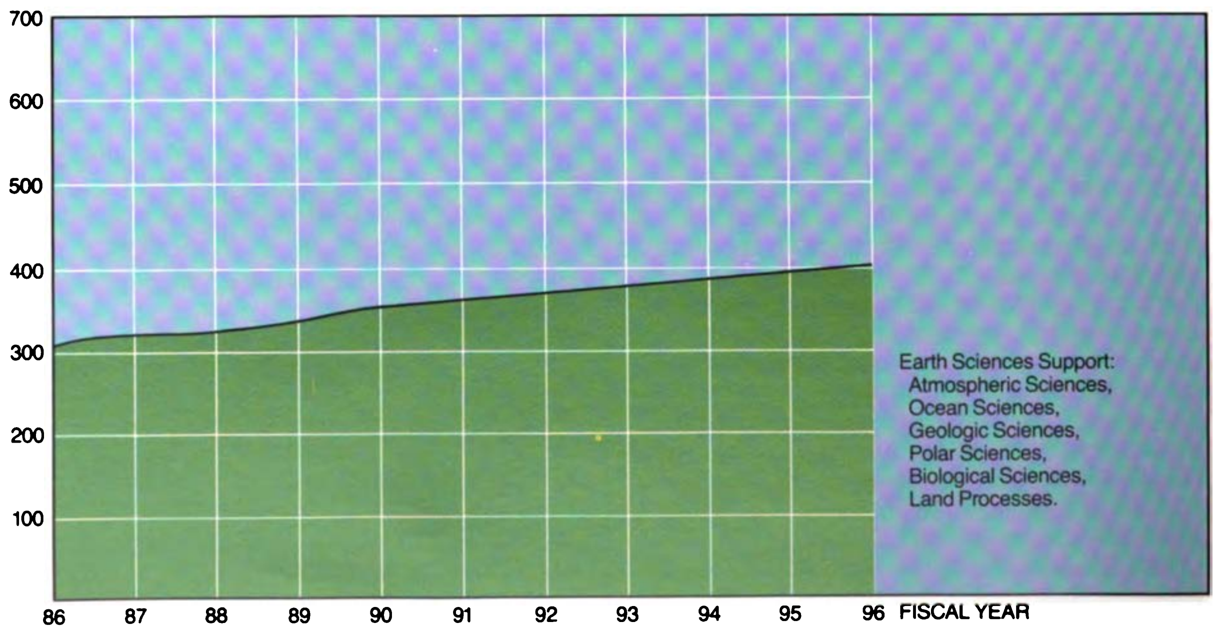

Figure 6. ESSC ESTIMATE OF NSF BUDGET (FY 1986 dollars, in millions).

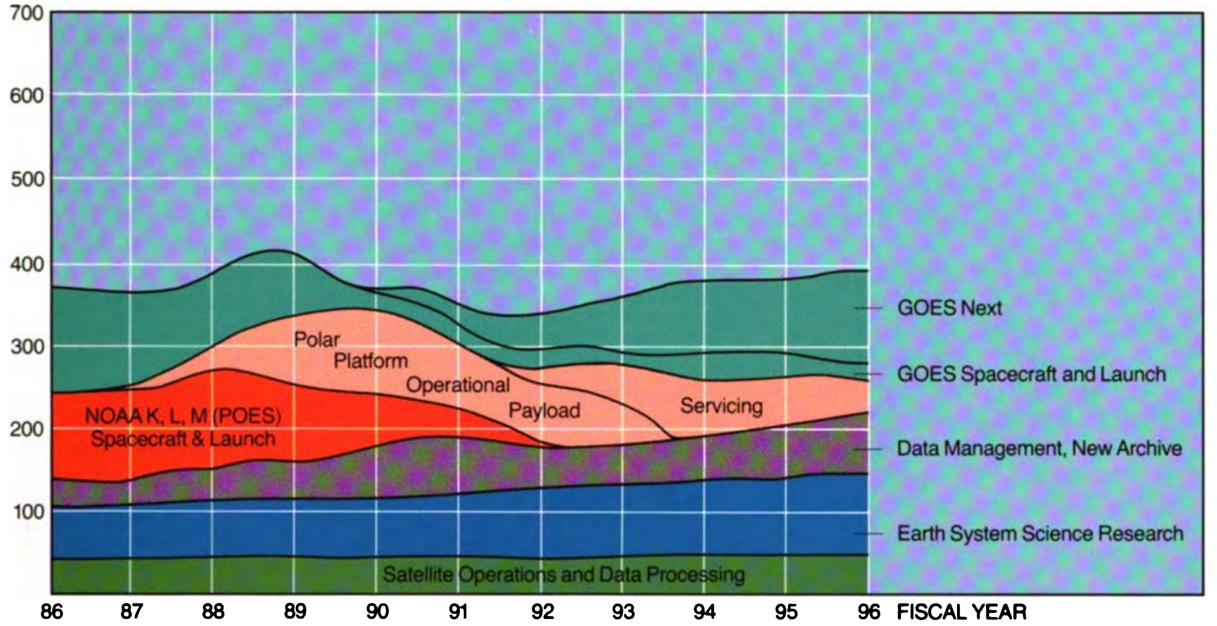

Figure 7. ESSC ESTIMATE OF NOAA BUDGET (FY 1986 dollars, in millions).

that in the long run is comparable to the average level of recent years in real terms. This expectation is based on reductions in cost to NOAA which can be realized through NOAA use of the polar platforms, together with increased foreign contributions to an operational program which is of wide international benefit.

Several important steps toward implementation of the recommended program may be taken in the near term at little or no additional cost. Within the agencies, program managers should seek to emphasize research that promotes studies of the interactions among the Earth's components; this reorientation of research emphasis can be accomplished rather quickly, and within present funding levels. The strengthening of interagency and international relationships, which in any case must begin at once, represents another area in which rapid progress can be made at modest expense.

CONCLUDING REMARKS

We are privileged to live in an extraordinary age of scientific research. We are probing the structure of the fundamental particles of matter, unraveling the genetic code of life, exploring the planets of our Solar System, and pushing back the frontiers of astronomy to the beginning of the Universe.

It is no less wonderful to study the Earth. It is also essential, for it is where we live.

The primary task of the Earth System Sciences Committee was to define a robust, long-term implementation strategy for the study of the Earth from space, supported by appropriate *in situ* measurements. In the course of its work, the Committee confirmed that the study of the Earth as an integrated system of closely interacting components indeed furnishes a unifying principle to guide such an investigation. The present, two-year study of Earth System Science brought together representatives from a wide variety of Earth-science disciplines and helped to establish new channels of communication and understanding among them. As a result, the approach of Earth System Science is rapidly becoming supported by a broad consensus throughout the Earth-science community.

The near-term program of space missions recommended here incorporates projects that have already been carefully studied and strongly recommended by other groups. However, the integrated program recommended by ESSC places these within the framework of a systematic and rational approach to the study of the Earth as a whole. Also required in the near term is an advanced information system and an expanded research effort in specific areas, such as biology, that cannot yet take full advantage of space observations. When complemented by appropriate *in situ* measurements, the near-term space program lays the scientific foundation for the recommended global Earth observing program and advanced information system for the longer term.

New space technology is clearly important to the initiatives recommended here, above all the development of a next generation of polar-orbiting space platforms that offer extensive technical capabilities and the opportunity for Space Shuttle servicing. Platforms meeting these requirements are currently planned as part of the Space Station Complex and are essential for implementing NASA's proposed Earth Observing System in the Space Station era. NASA will need to continue to lead the development of this and other important space technology.

The Committee also considered in detail the roles of Federal agencies in this effort. An effective collaboration between NASA and NOAA is particularly important to the implementation of the space component of the recommended program. For example, operational data processed and archived by NOAA need to be made more accessible to the scientific community, and a full utilization of the future Earth Observing System will require the simultaneous spaceflight of NASA research missions and NOAA operational missions on polar and geosynchronous platforms. Because of the importance of complementary *in situ* measurements and broad programs of basic research, NSF will need to play a leadership role as well. Many other Federal agencies should also participate in an integrated program of Earth System Science.

The issues of management and leadership emerge as key to the success of Earth System Science. Federal agencies will need to develop new mechanisms for effective collaboration, so that the United States contribution to Earth System Science may be developed in an integrated manner. However, the global study of the Earth is an inherently international undertaking. We must continue to pursue the international agreements and coordination necessary for a truly worldwide program of Earth System Science.

APPENDIX A

RECENT REPORTS RELEVANT TO EARTH SYSTEM SCIENCE

A Strategy for Earth Science from Space in the 1980's, Part I: Solid Earth and Oceans. Committee on Earth Sciences of the Space Science Board, National Research Council (National Academy Press, Washington, D.C., 1982).

A Strategy for Earth Science from Space in the 1980's, Part II: Atmosphere and Interactions with the Solid Earth, Oceans, and Biota. Committee on Earth Sciences of the Space Science Board, National Research Council (National Academy Press, Washington, D.C., 1985).

Global Change in the Geosphere-Biosphere: Initial Priorities for an IGBP. U.S. Committee for an International Geosphere-Biosphere Program of the Commission on Physical Sciences, Mathematics, and Resources, National Research Council (National Academy Press, Washington, D.C., 1986).

Global Change: Impacts on Habitability, A Scientific Basis for Assessment. (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1982)

Towards a Science of the Biosphere. Committee on Planetary Biology of the Space Science Board, National Research Council (To be published by the National Academy of Sciences).

Solar-System Space Physics in the 1980's: A Research Strategy. Committee on Solar and Space Physics of the Space Science Board, National Research Council (National Academy Press, Washington, D.C., 1980).

An Implementation Plan for Priorities in Solar-System Space Physics. Committee on Solar and Space Physics of the Space Science Board, National Research Council (National Academy Press, Washington, D.C., 1985).

Planetary Exploration Through Year 2000. Solar System Exploration Committee of the NASA Advisory Council (National Aeronautics and Space Administration, Washington, D.C., 1983).

Earth Sciences Research in the Civil Space Program. Office of Science and Technology Policy of the Executive Office of the President (Washington, D.C., October 1985).

APPENDIX B

ACRONYMS AND ABBREVIATIONS

ACR: Active Cavity Radiometer
ATMOS: Atmospheric Trace Molecules Observed by Spectroscopy
CEOS: Committee on Earth Observations Satellites
COSEPUP: Committee on Science, Engineering, and Public Policy
DMSP: Defense Meteorological Satellite Program
DoD: Department of Defense
DoE: Department of Energy
DoI: Department of the Interior
Eos: Earth Observing System
EOSAT: The EOSAT Company
EPA: Environmental Protection Agency
ERB: Earth Radiation Budget
ERBE: Earth Radiation Budget Experiment
ERBS: Earth Radiation Budget Satellite
ESA: European Space Agency
ESSC: Earth System Sciences Committee
FEMA: Federal Emergency Management Agency
GARP: Global Atmospheric Research Program
GEMS: Global Environment Monitoring System
GEOSAT: Geodesy Satellite
GGM: Gravity Gradiometer Mission
GLRS: Geodynamics Laser Ranging System
GMS: Geostationary Meteorological Satellite
GOES: Geostationary Operational Environmental Satellite System
GOFS: Global Ocean Flux Study
GPS: Global Positioning System
GRID: Global Resource Information Database
GRM: Geopotential Research Mission
GTCP: Global Tropospheric Chemistry Program
ICSU: International Council of Scientific Unions
IGBP: International Geosphere-Biosphere Program
IOC: International Oceanographic Commission
IRS: Indian Remote Sensing satellite
ISCCP: International Satellite Cloud Climatology Project
ISLSCP: International Satellite Land Surface Climatology Project
JERS: Japan Earth Remote Sensing satellite
LAGEOS: Laser Geodynamics Satellite
LANDSAT: Land Remote Sensing Satellite
LIDAR: Light Detection and Ranging Instrument
MAPS: Measurement of Air Pollution from Shuttle
METEOR: Meteorological Satellite (USSR)
METEOSAT: Meteorology Satellite (ESA)
MFE: Magnetic Field Explorer
MOS: Marine Observation Satellite (Japan)
MTE: Magnetosphere-Thermosphere Explorer
NASA: National Aeronautics and Space Administration
NASDA: Japan Space Agency
NOAA: National Oceanic and Atmospheric Administration
N-ROSS: Navy Remote Ocean Sensing System
NSCAT: N-ROSS Scatterometer
NSF: National Science Foundation
OCI: Ocean Color Imager
POES: Polar Operational Environmental Satellite System
PSN: Piano Spaziale Nazionale (Italian National Space Plan)
RADARSAT: Radar Satellite (Canada)
SBUV: Solar Backscatter Ultraviolet spectrometer
SEASAT: Sea Satellite
SIR: Shuttle Imaging Radar
SISEX: Shuttle Imaging Spectrometer Experiment
SPOT: Système Probatoire d'Observation de la Terre
SUSIM: Solar Ultraviolet Spectral Irradiance Monitor
TOGA: Tropical Ocean Global Atmosphere Program
TOPEX/POSEIDON: Ocean Topography Experiment (U.S./France).
UARS: Upper Atmosphere Research Satellite
UN: United Nations
UNEP: United Nations Environment Program
UNESCO: United Nations Educational, Scientific, and Cultural Organization
USDA: United States Department of Agriculture
USGS: United States Geological Survey
VLBI: Very Long Baseline Interferometry
WCRP: World Climate Research Program
WMO: World Meteorological Organization
WOCE: World Ocean Circulation Experiment
WWW: World Weather Watch

APPENDIX C

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