A PROGRAM FOR GLOBAL CHANGE

Earth System Science

Overview

This approach is rapidly gaining the support of scientists from a wide variety of traditional Earth-science disciplines.

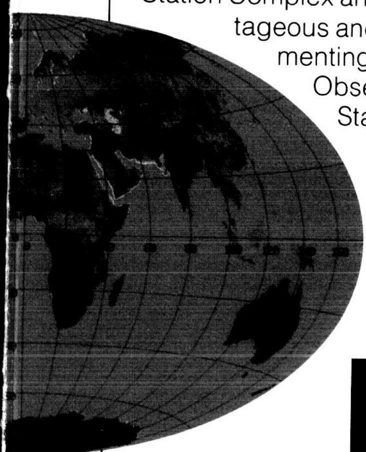
◆ **Defined an integrated program for Earth investigations from space** that (1) builds upon two decades of successful research and operational satellites, and (2) places currently planned near-term missions within the framework of a systematic approach to the study of the Earth as a whole. This near-term space program, complemented by appropriate *in situ* measurements, furthermore lays the scientific foundation for the recommended global observing program and associated information system in the longer term.

◆ **Confirmed the importance of new space technology** for the study of the Earth as a system, especially a next generation of large space platforms in polar orbit. Such platforms are currently planned as part of the U.S. Space Station Complex and would be both advantageous and cost-effective for implementing the proposed Earth Observing System in the Space Station era.

◆ **Considered the roles of NASA, NOAA and the National Science Foundation (NSF)** in an integrated Earth System Science research program, calling particular attention to the need for these agencies to collaborate closely in future studies of the Earth System. The important roles of other Federal agencies are also recognized.

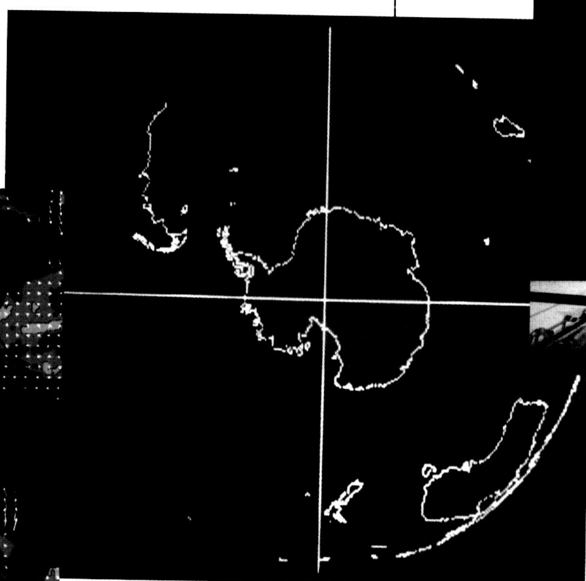
◆ **Identified the issues of management and leadership** as key to the success of these initiatives. United States agencies will need to develop new mechanisms for interacting and carrying out the Federal research program outlined here. Moreover, the success of Earth System Science will also require a collective research effort by the nations of the Earth. Any U.S. program must be part of an effective international collaboration in Earth remote sensing systems and other research activities.

EARTH OBSERVING SYSTEM



WORLDWIDE VEGETATION PATTERNS

SPACE CONSTRUCTION



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Preface

In 1983, the Advisory Council of the National Aeronautics and Space Administration (NASA) established an Earth System Sciences Committee (ESSC) to:

◆ Review the science of the Earth as an integrated system of interacting components;

◆ Recommend an implementation strategy for global Earth studies; and

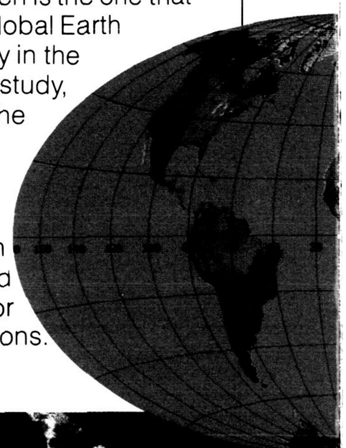
◆ Define NASA's role in such a program of Earth System Science.

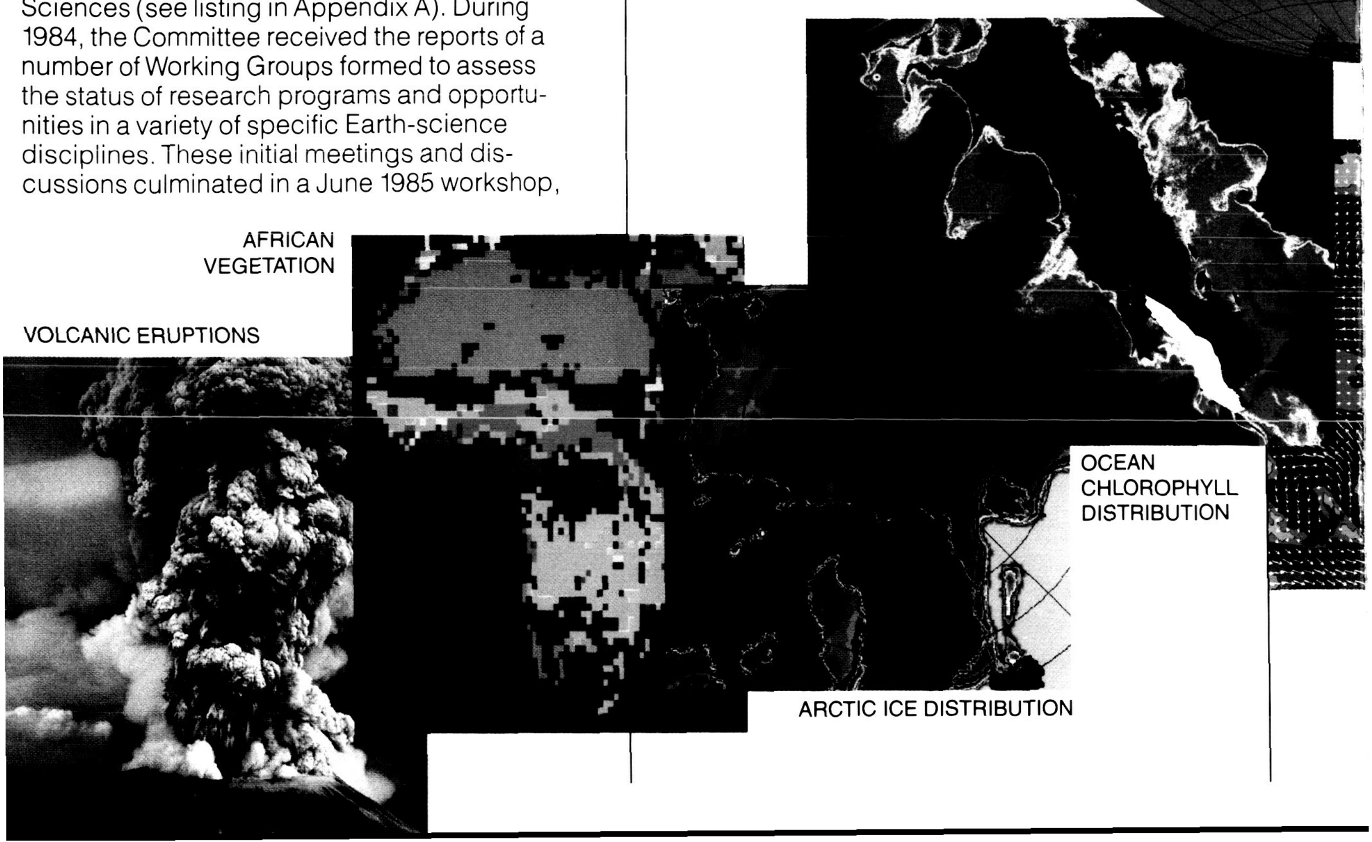
In charging the Committee with these tasks, the Council emphasized the importance of understanding the Earth as a system, within the context of the solar environment, and of an integrated research program for the study of global change. Both of these objectives are highly relevant to the future habitability of the Earth. In view of the strong collaborative role to be played by the National Oceanic and Atmospheric Administration (NOAA) in any program of Earth System Science, NOAA has requested that it also receive the Committee's recommendations. The present report is thus addressed to NASA and NOAA jointly.

The Committee began its deliberations in November 1983 with a review of other relevant reports and studies, particularly those of the Space Science Board of the National Academy of Sciences, and a consideration of concurrent approaches to the investigation of global change, such as the Global Habitability study of NASA and the International Geosphere-Biosphere study of the National Academy of Sciences (see listing in Appendix A). During 1984, the Committee received the reports of a number of Working Groups formed to assess the status of research programs and opportunities in a variety of specific Earth-science disciplines. These initial meetings and discussions culminated in a June 1985 workshop, during which the Committee achieved a consensus on an implementation strategy for Earth System Science for the next 10-15 years. The present study is believed to mark the first time that such a large and disparate group of Earth scientists, representing broad areas of Earth study, has attempted to define a unified, systematic approach to the scientific investigation of the entire Earth.

A research strategy for all of Earth science — one that would assign research priorities across all discipline boundaries and among all measurement techniques — is not yet within reach. The Earth System Sciences Committee followed a more restricted approach, first identifying those research areas to which space techniques and observations can make an outstanding contribution, and then considering the *in situ* activities and measurements necessary to support and complement the observations from space. Because of the unique benefits of the space perspective, this approach is the one that seems most likely to advance global Earth studies both broadly and rapidly in the years ahead. In the course of its study, the Committee accomplished the following:

◆ **Identified a unifying scientific strategy** by confirming that the concept of the Earth as an integrated system indeed provides strategic guidance for future Earth-science investigations.





AFRICAN VEGETATION

VOLCANIC ERUPTIONS

OCEAN CHLOROPHYLL DISTRIBUTION

ARCTIC ICE DISTRIBUTION

We, the peoples of the world,

face a new responsibility for our global future. Through our economic and technological activity, we are now contributing to significant global changes on the Earth within the span of a few human generations. We have become part of the Earth System and one of the forces for Earth change.

Research holds the key to a deeper understanding of the Earth as an integrated system of interacting components, and of the consequences of global change for humanity. To achieve this understanding, the Earth System Sciences Committee recommends:

OVER THE NEXT DECADE—

◆ **Programs of continuing and operational space observations** to extend and to enhance those presently being carried out by the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and others;

◆ **A coordinated sequence of specialized space research missions** for studies of specific Earth System processes, including the
- Earth Radiation Budget Experiment (ERBE, launched 1984),
- Laser Geodynamics Satellites (LAGEOS-1, launched 1976, and LAGEOS-2, started 1983),
- Upper Atmosphere Research Satellite (UARS, started 1982),
- Navy Remote Ocean Sensing System (N-ROSS, started 1985),
- Ocean Topography Experiment (TOPEX/POSEIDON, candidate new start 1987), and
- Geopotential Research Mission (GRM, candidate new start 1989);

◆ **Pursuit of other observing opportunities** to obtain important Earth System data at modest additional cost;

◆ **An interdisciplinary program of basic Earth System research and *in situ* measurements** to be carried out by NASA, NOAA, the National Science Foundation (NSF), and other Federal agencies;

◆ **An advanced information system** to process global data and to facilitate data analysis, data interpretation, and quantitative modeling of Earth System processes by the scientific community; and

◆ **A program of instrument development** to ready a variety of satellite experiments for implementation in the mid-1990's.

DURING THE SPACE STATION ERA: MID-1990's AND BEYOND—

◆ **An Earth Observing System** utilizing polar-orbiting platforms planned as part of the U.S. Space Station program and offering opportunities for combined flight of NASA research instruments and NOAA operational payloads, to provide continuous, long-term global Earth observations (candidate NASA new start, 1989);

◆ **Advanced geostationary space platforms** to support a new generation of research and operational measurements from geosynchronous orbit; and

◆ **Additional specialized space research missions,** including the
- Rainfall Mission (candidate new start 1991),
- Magnetic Field Explorer (MFE, candidate new start 1993),
- Mesosphere-Thermosphere Explorer (MTE, candidate new start 1995), and
- Gravity Gradiometer Mission (GGM, candidate new start 1997).

BEGINNING AT ONCE—

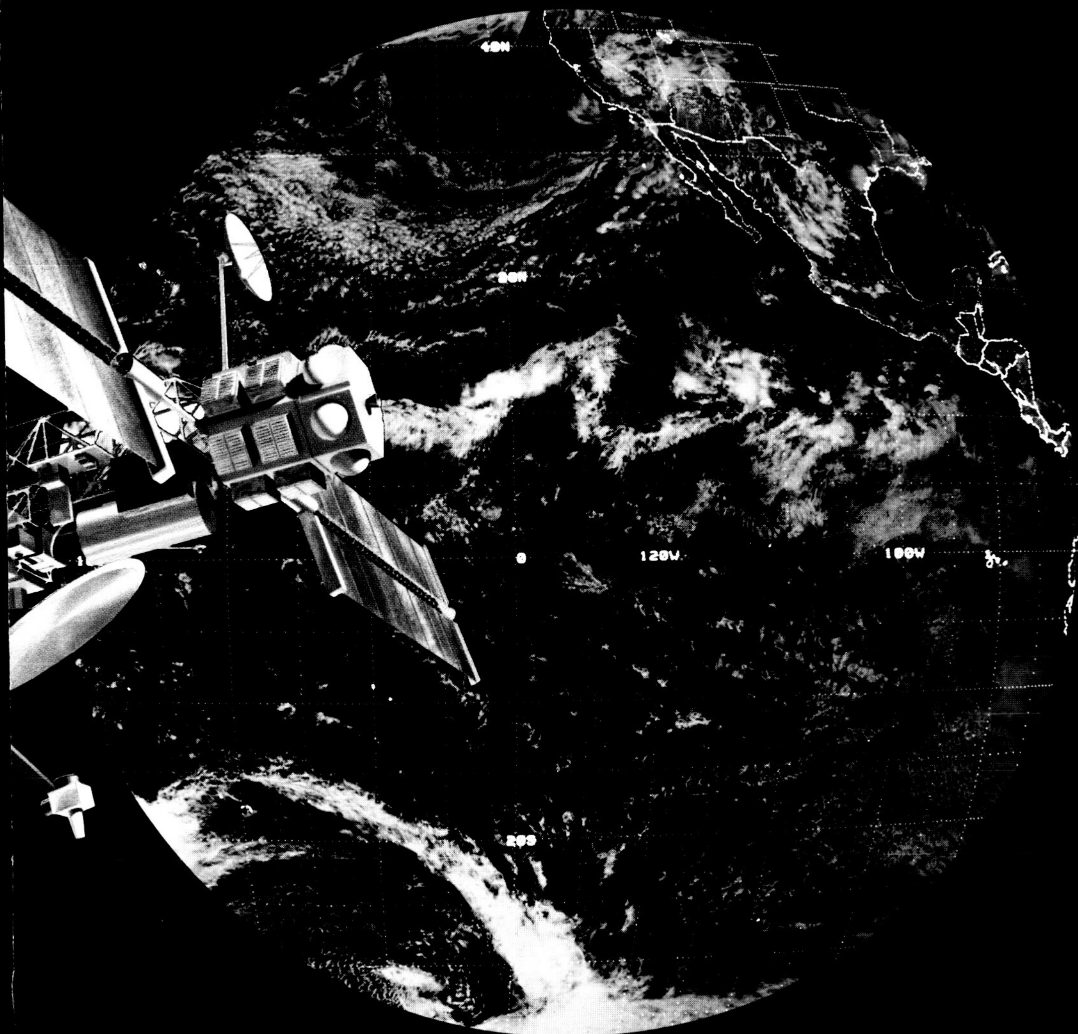
◆ **Development of new management policies and mechanisms** to foster cooperation among NASA, NOAA, NSF, other Federal agencies and commercial firms engaged in Earth System Science and the study of global change; and

◆ **Strengthening of the international agreements and coordination** necessary for a truly worldwide study of the Earth.

Each of these steps will contribute to a new framework for Earth studies. By deciding to take these steps now, we can help to ensure that the gifts of the Earth will be preserved and passed on to future generations.

Earth System Science
Overview

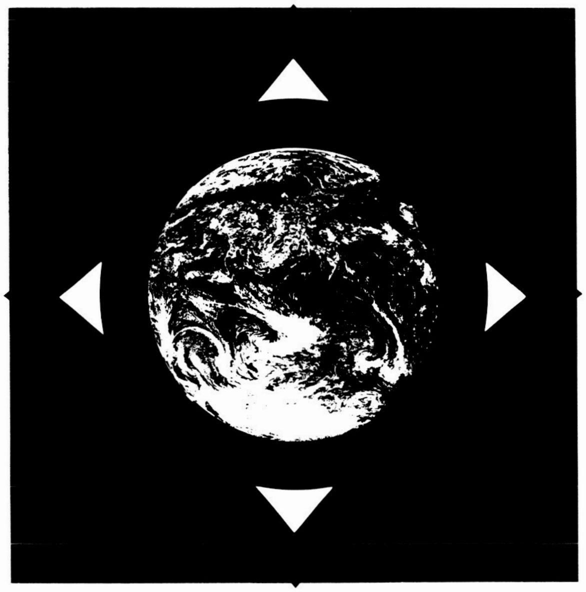
A PROGRAM FOR GLOBAL CHANGE

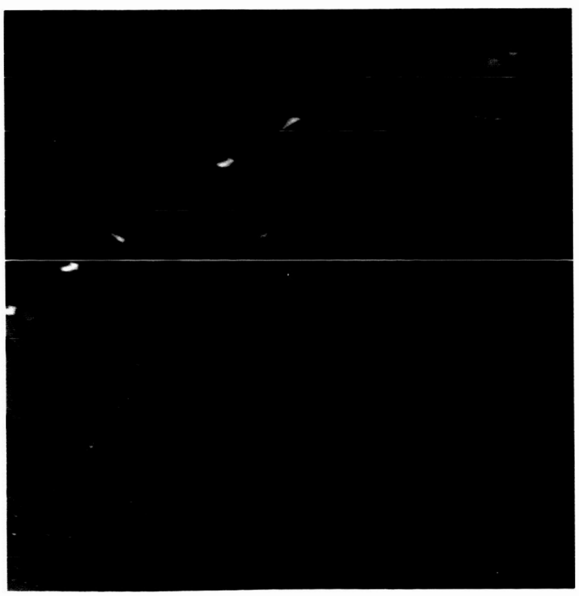


Prepared by the
Earth System Sciences Committee
NASA Advisory Council

National Aeronautics and Space Administration

Contents





INTRODUCTION 4

OUR PLANET EARTH 9

THE EARTH SCIENCES 9

SCIENCE FOR PRACTICAL BENEFITS 9

A NEW HUMAN NEED:
STUDY OF GLOBAL CHANGE 10

THE EARTH AND THE SOLAR SYSTEM 13

EARTH SYSTEM SCIENCE 15

THE SOLID EARTH 15

THE FLUID AND BIOLOGICAL EARTH 17

MODELING THE EARTH SYSTEM 20

ATMOSPHERE-OCEAN INTERACTION 20

THE CENTRAL APPROACH AND
THEMES OF EARTH SYSTEM SCIENCE . . 21

THE GOAL OF EARTH SYSTEM SCIENCE . . 26

THE CHALLENGE TO
EARTH SYSTEM SCIENCE 26

ROLE OF SPACE OBSERVATIONS 27

TWO PROGRAM PATHS 27

EXAMPLES OF
REQUIRED MEASUREMENTS 28

A FUTURE PROGRAM OF
EARTH OBSERVATIONS 29

RESEARCH BRIEFING BY THE
NATIONAL ACADEMY OF SCIENCES . . . 29

THE RECOMMENDED PROGRAM 31

PRIORITIES FOR AN
IMPLEMENTATION STRATEGY 31

THE CURRENT ERA 31

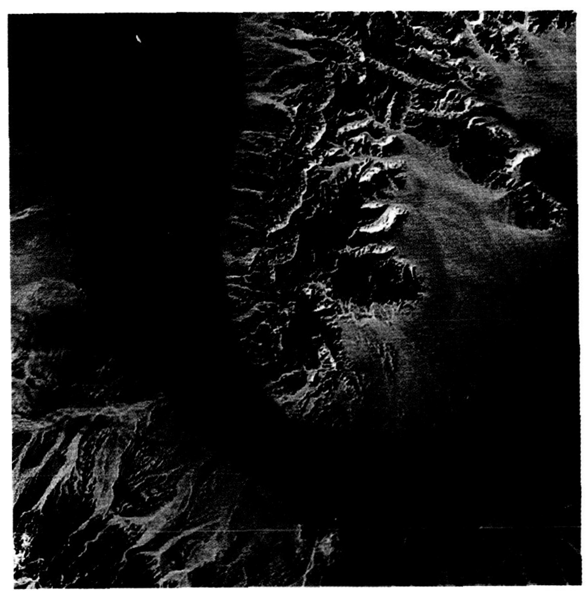
THE SPACE STATION ERA 37

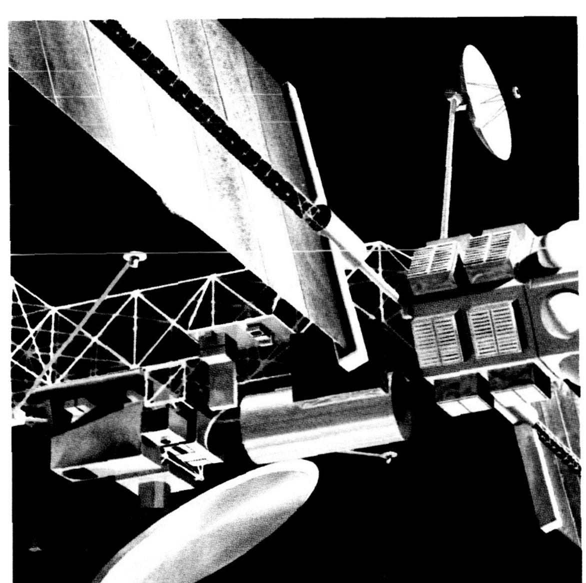
UNITED STATES AGENCY ROLES 40
INTERNATIONAL COOPERATION 43
BUDGET ESTIMATES 44
CONCLUDING REMARKS 46

FIGURE 1: Earth System Processes: Characteristic Space and Time Scales 16
FIGURE 2a: Solid Earth Processes 18
FIGURE 2b: Fluid and Biological Earth Processes 19
FIGURE 3: Fluid and Biological Earth Processes: Detailed Information Flow 24
FIGURE 4: Earth System Science Through the Year 2000 38
FIGURE 5: ESSC Estimate of NASA Budget . . . 44
FIGURE 6: ESSC Estimate of NSF Budget 44
FIGURE 7: ESSC Estimate of NOAA Budget . . 45

TABLE 1A: Observational Programs for Global Data Acquisition: Representative Examples of Approved and Continuing Programs 34
TABLE 1B: Observational Programs for Global Data Acquisition: Representative Examples of Proposed Future Programs 35
TABLE 2: Representative Examples of Proposed Satellite Measurements 40

APPENDIX A: Recent Reports Relevant to Earth System Science 47
APPENDIX B: Acronyms and Abbreviations . . 47
APPENDIX C: ESSC Membership; Liaisons; Acknowledgements 48





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.

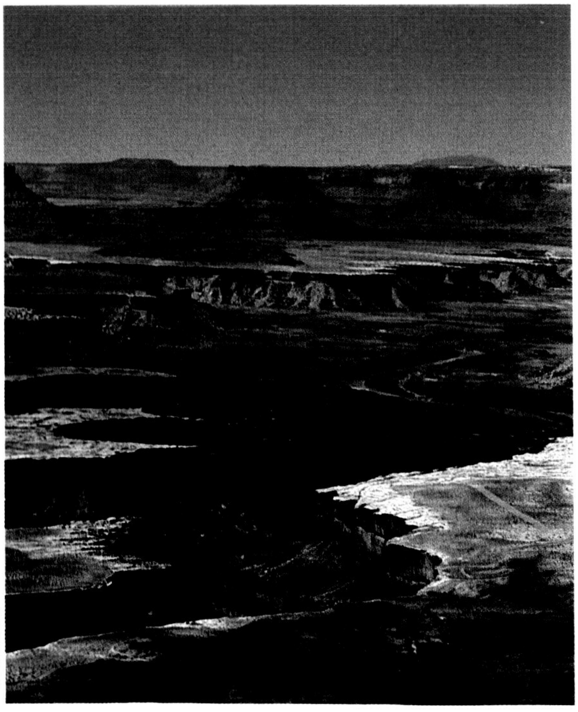
The Challenge to Earth System Science

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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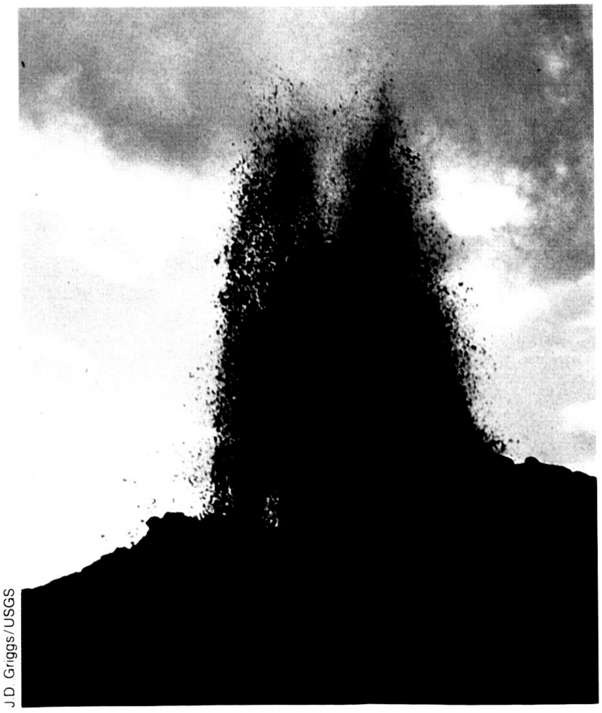


J.D. Griggs/USGS

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.

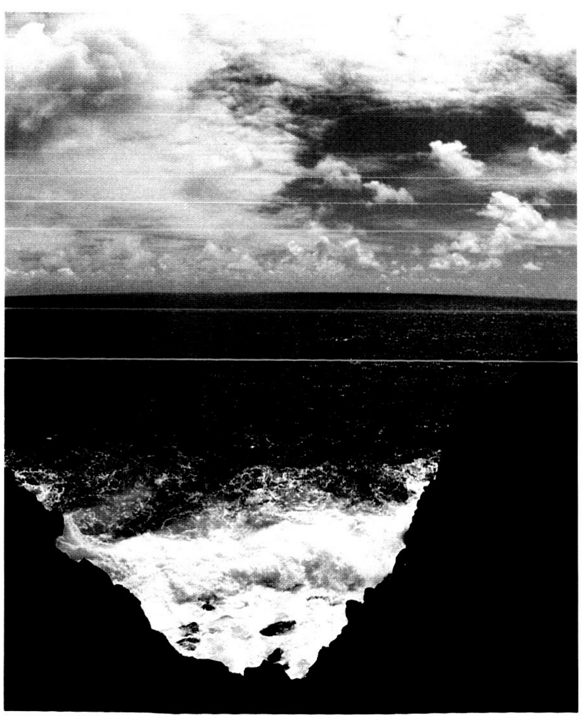
We particularly require a set of Earth observations that will permit us to disentangle the complex interactions among the Earth's components and to document their effects over extended time periods. Such observations will allow us to establish causal relationships among the processes involved and therefore 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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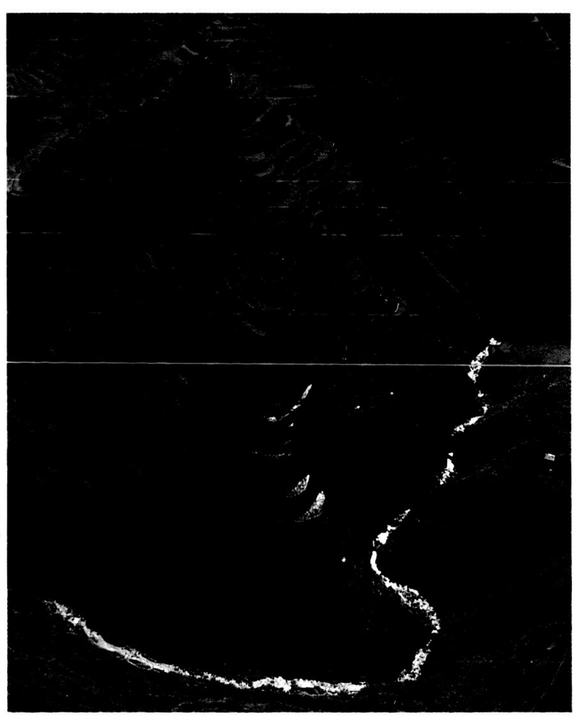

Bruce Dale ©National Geographic Society

◆ **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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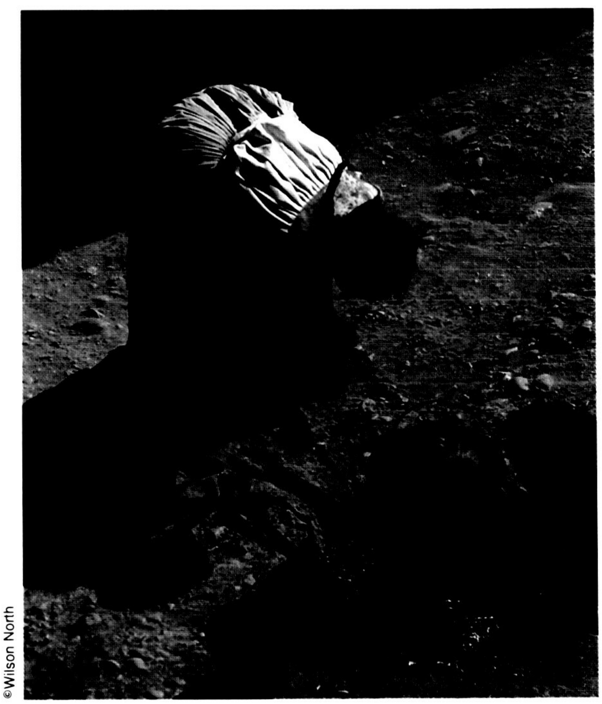

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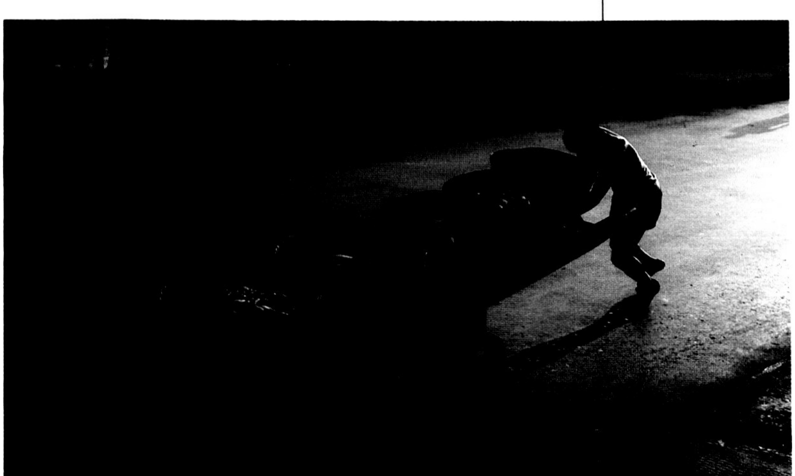

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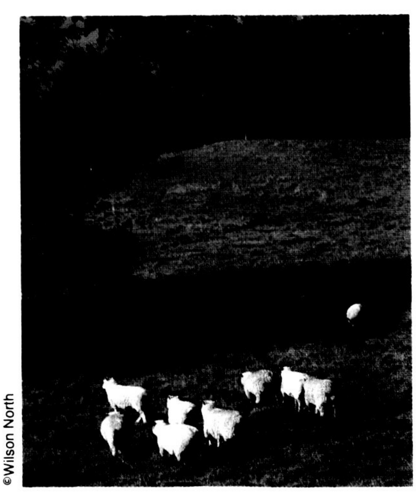

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We have no greater concern than the future of this planet and the life upon it. Exploration of the other planets in the Solar System has confirmed the very special place of our world among them: the only planet with a biosphere, the only planet with 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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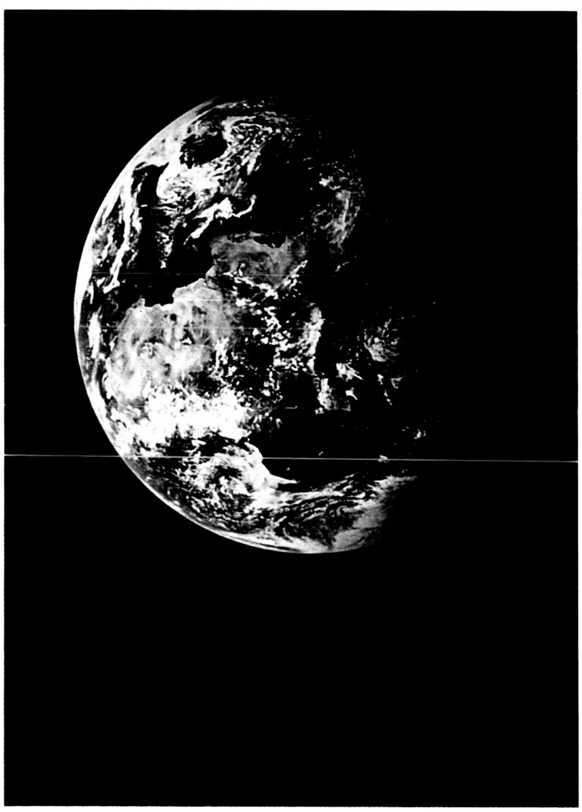

NASA

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

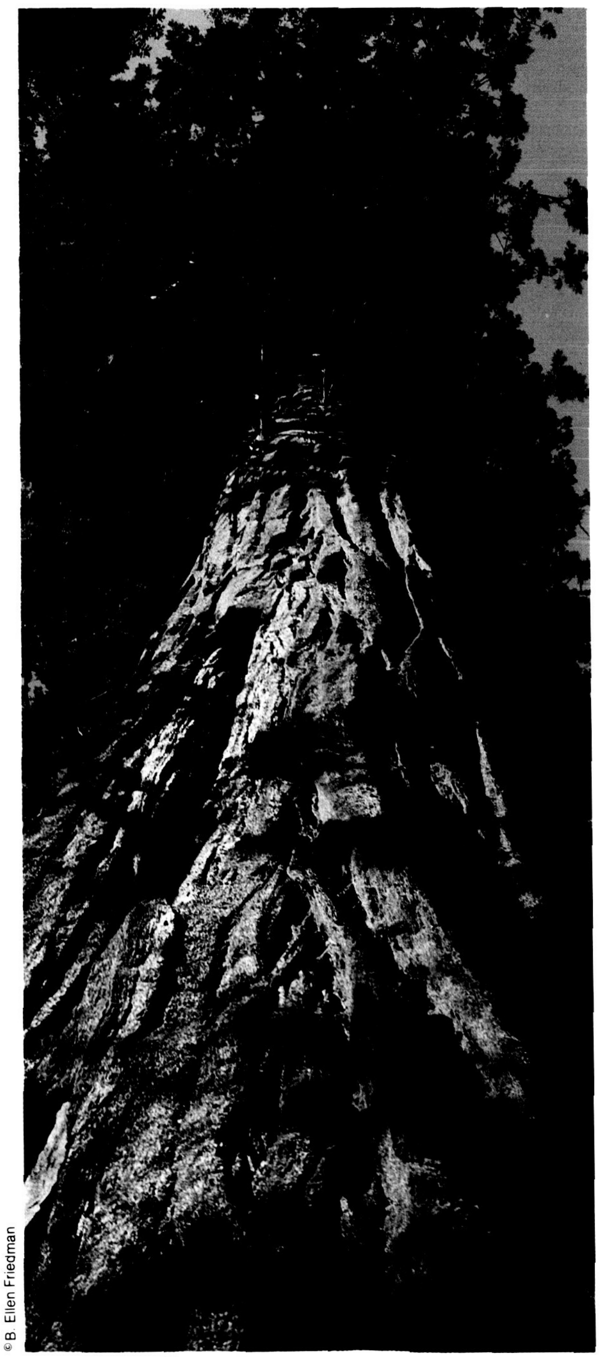
The pursuit of an improved quality of life upon the Earth goes hand in hand with the search for greater scientific understanding of the Earth itself. The application of basic research to human needs is today proceeding more vigorously than ever before.

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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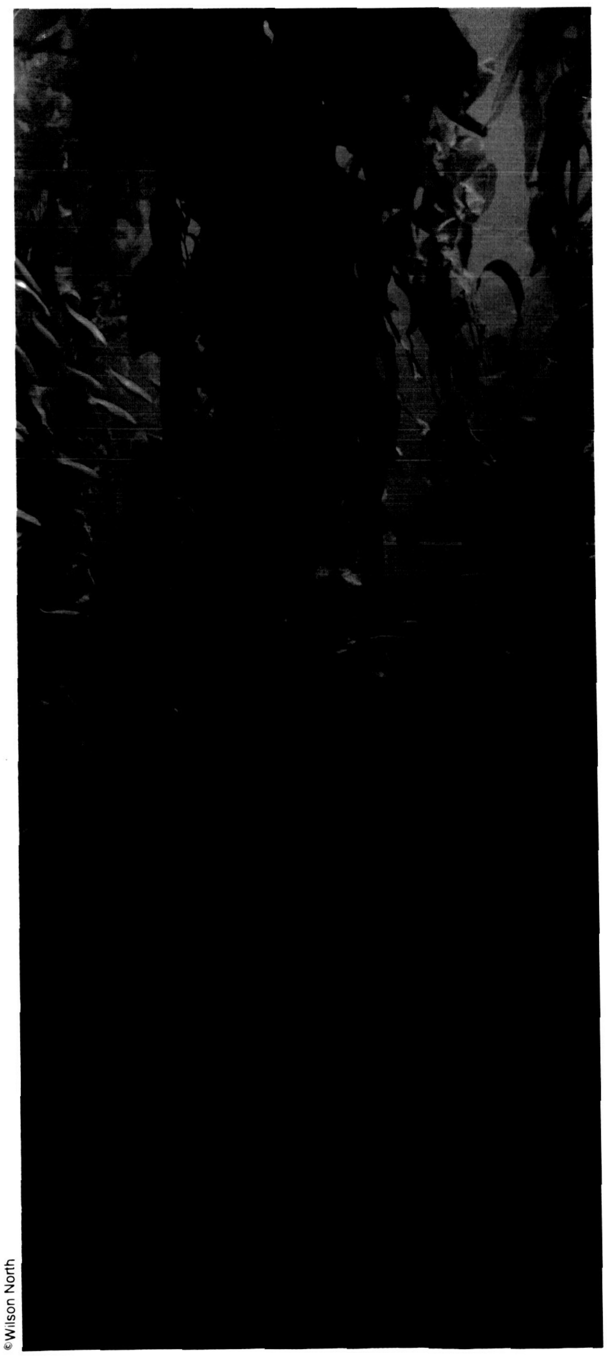

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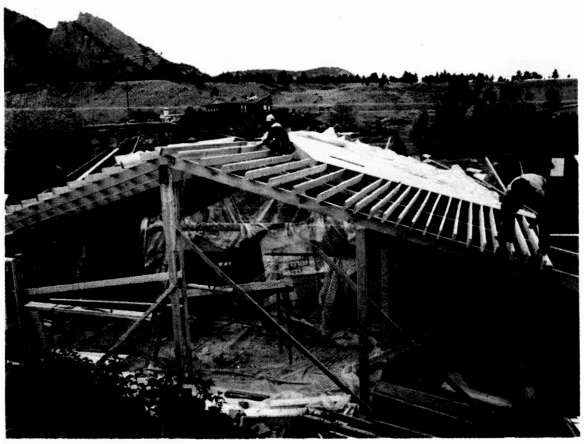
tions of these trace species are presently much less than that of carbon dioxide, they are rising much more rapidly. Their effects can also be more pronounced: molecule for molecule, chlorofluorocarbons produce 10,000 times the greenhouse effect of carbon dioxide, in addition to depleting stratospheric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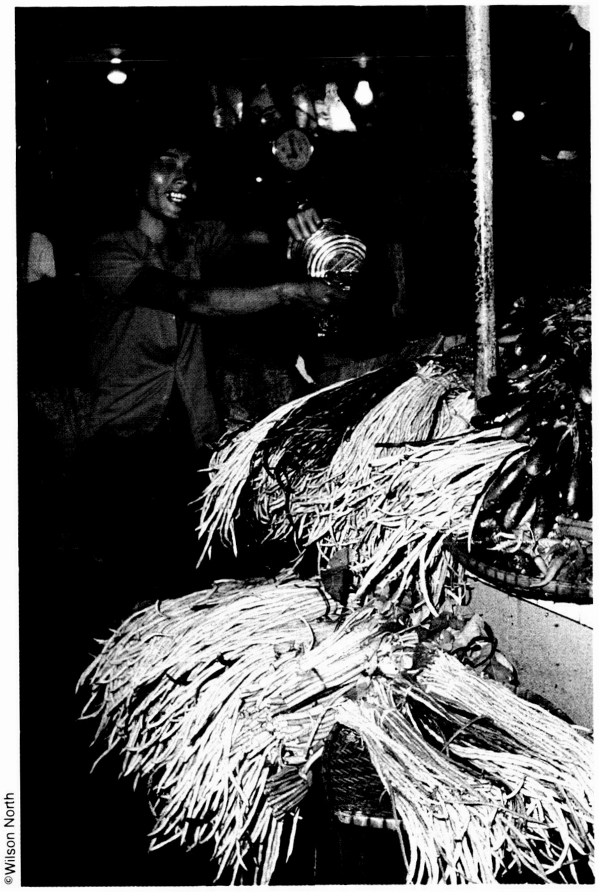

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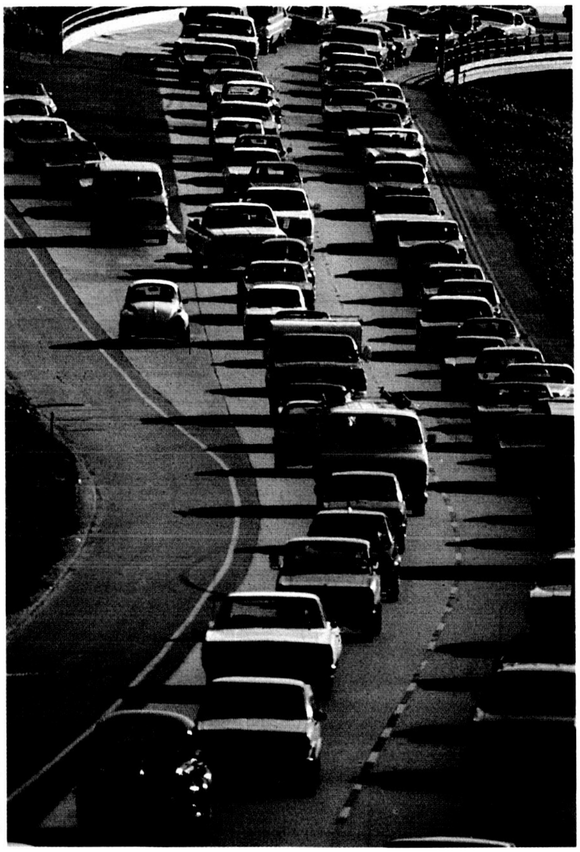
deforested land is planted to other vegetation, and since substantial afforestation may be occurring at northern midlatitudes, the net effect on carbon-dioxide balance remains unclear, but such changes are almost certain to alter the ecology of the land in a variety of ways. For example, the clearing 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.



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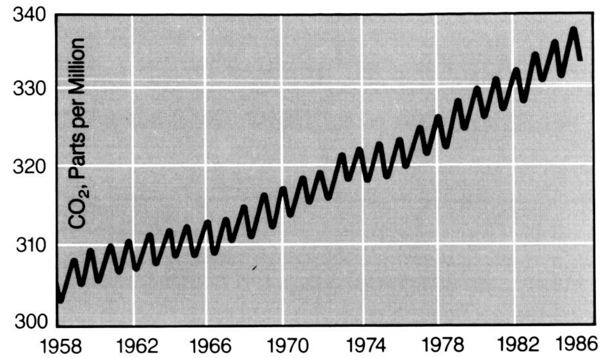
All of these human-induced changes are difficult to assess and measure accurately, but it is already evident that they are playing a role in shaping present and future global conditions. Now is the time to document these processes on a global scale and to identify the causal relationships among them,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

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



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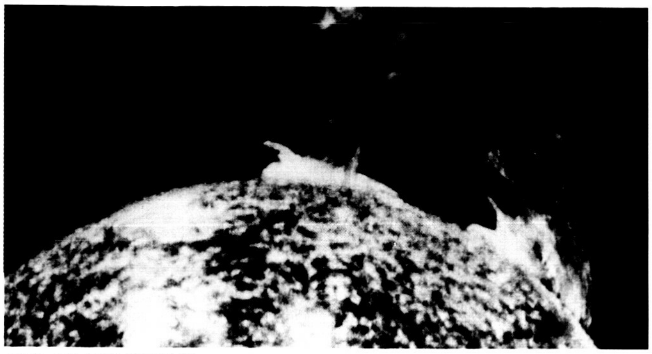

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SOLAR ERUPTION.

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AURORA BOREALIS.

The Earth and the Solar System

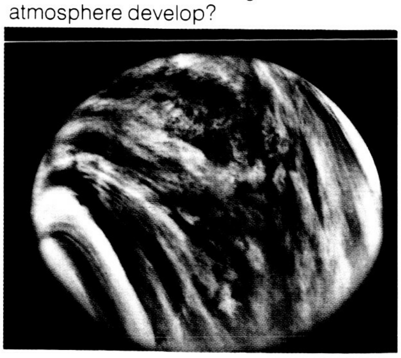
Any systematic approach to Earth studies must consider the Earth's membership in the Solar System — particularly the influence of the Sun and the coupling of the Earth to the space plasma of the heliosphere through its magnetosphere. As a matter of practical convention, the Earth System is here defined 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.

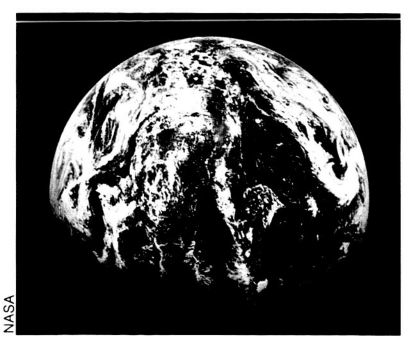
THE EARTH AND ITS VERY DIFFERENT NEIGHBORS.

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

Mars: Has liquid water ever flowed upon its surface?



NASA



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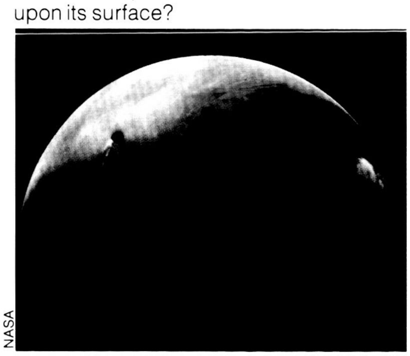


NASA

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

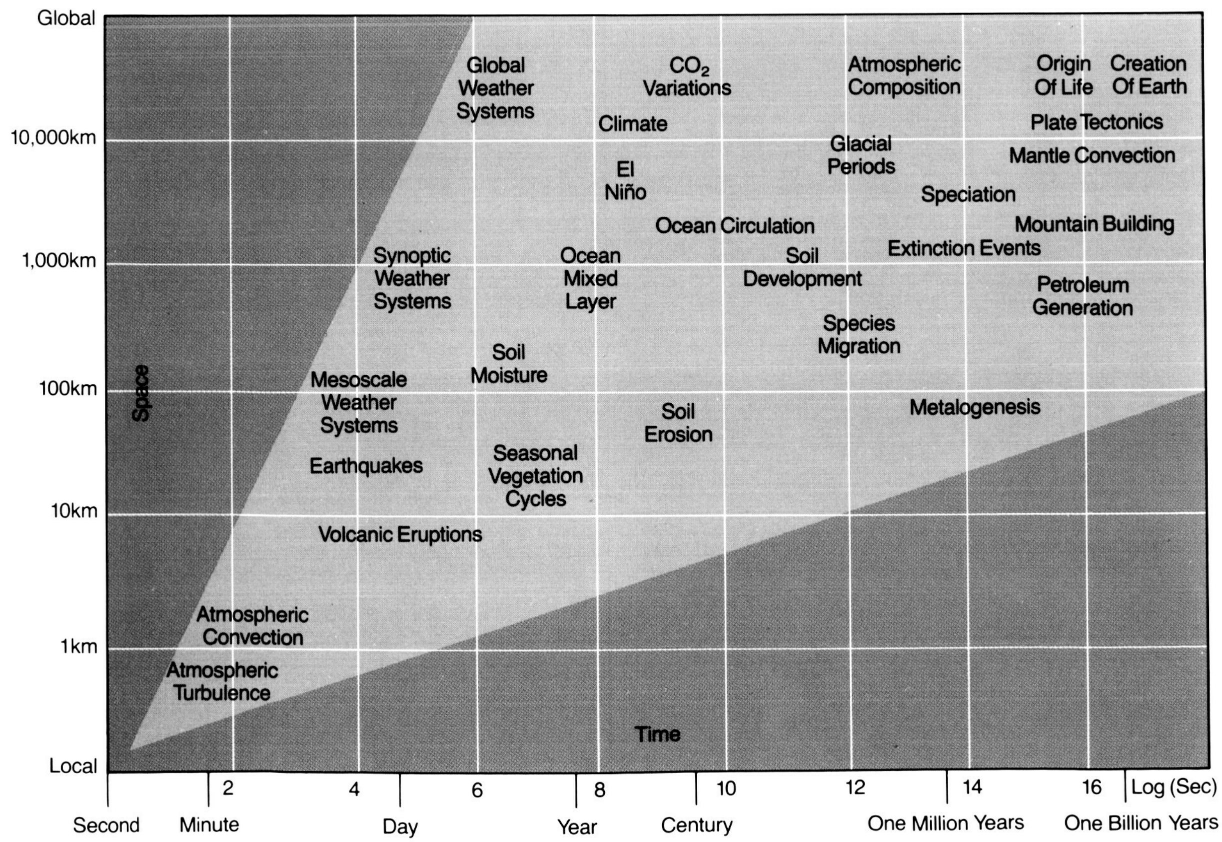
The thermal and compositional structure of the Earth's core, together with the dynamo mechanism responsible for the Earth's magnetic field, remain obscure in detail. We cannot predict the short-term changes in the geomagnetic field observed at the Earth's surface or explain why this field undergoes sporadic 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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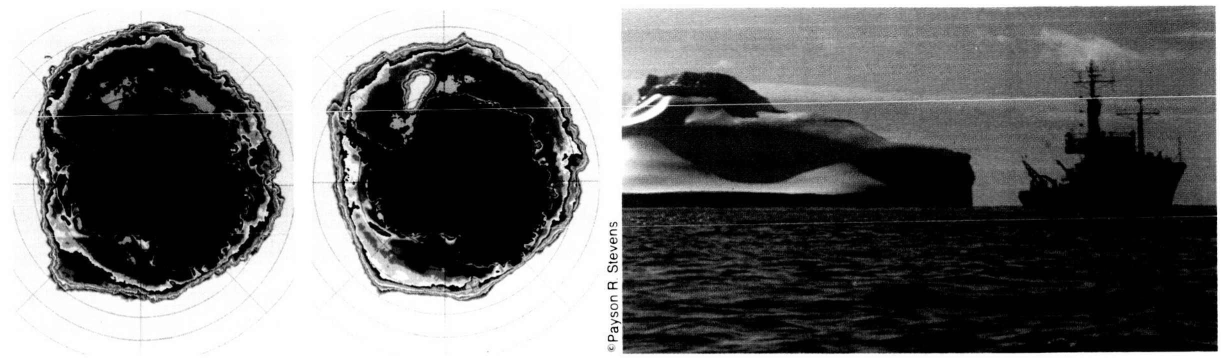
MODERN STROMATOLITES. These shallow-water constructions are produced by photosynthetic marine organisms that have helped shape the composition of the Earth's atmosphere by giving off oxygen.



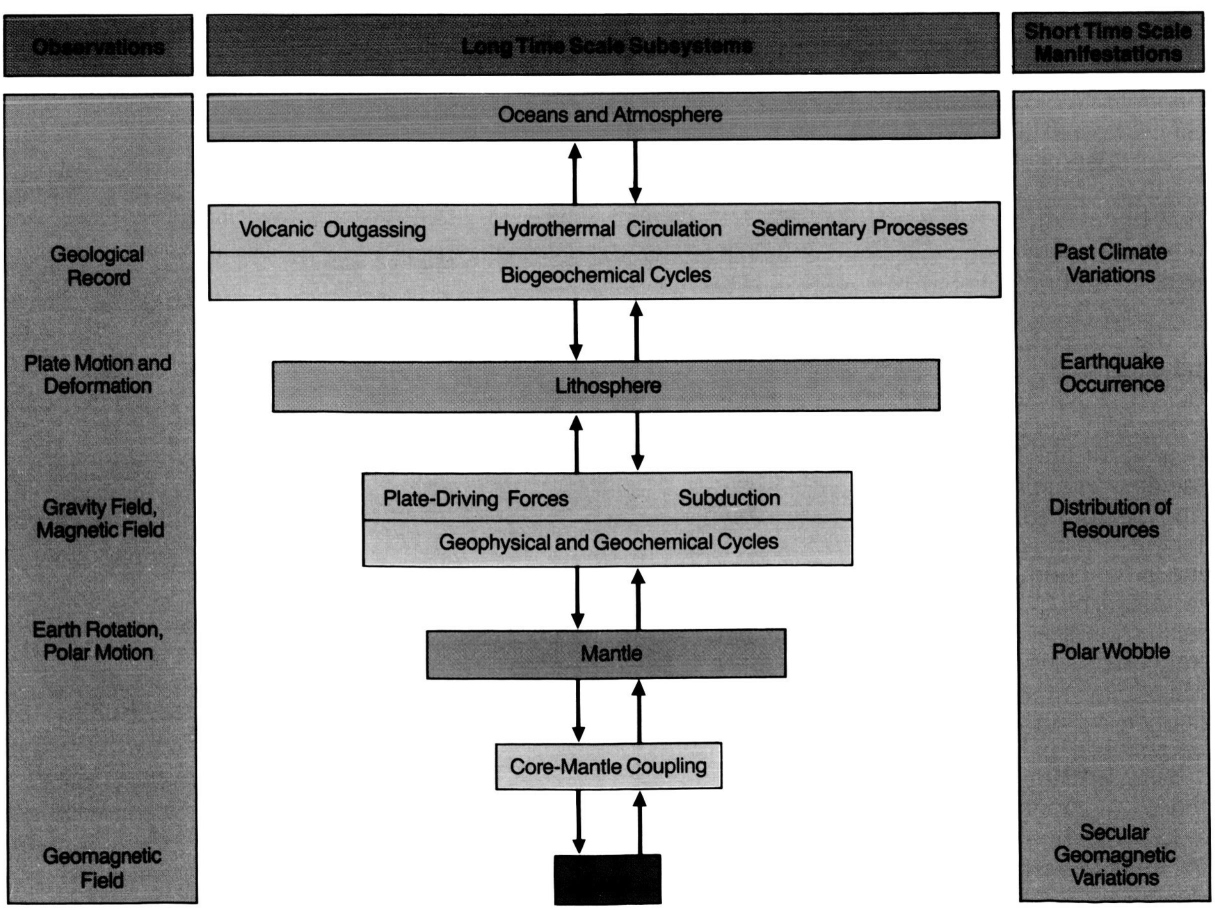
SATELLITE OBSERVATIONS OF ANTARCTIC SEA ICE COVER record interannual variations important to climate studies (far left, 1973, near left, 1976). Research vessels (right) provide *in situ* observations of related oceanographic features.

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

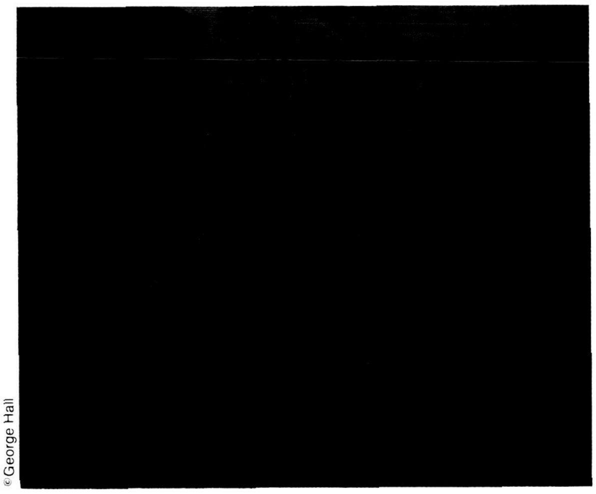


entering the atmosphere at accelerating rates; together with carbon dioxide, these gases are expected to cause important changes in global climate during the next century. They are emitted in the course of biological or human activity on land and in the oceans through processes that are still not well 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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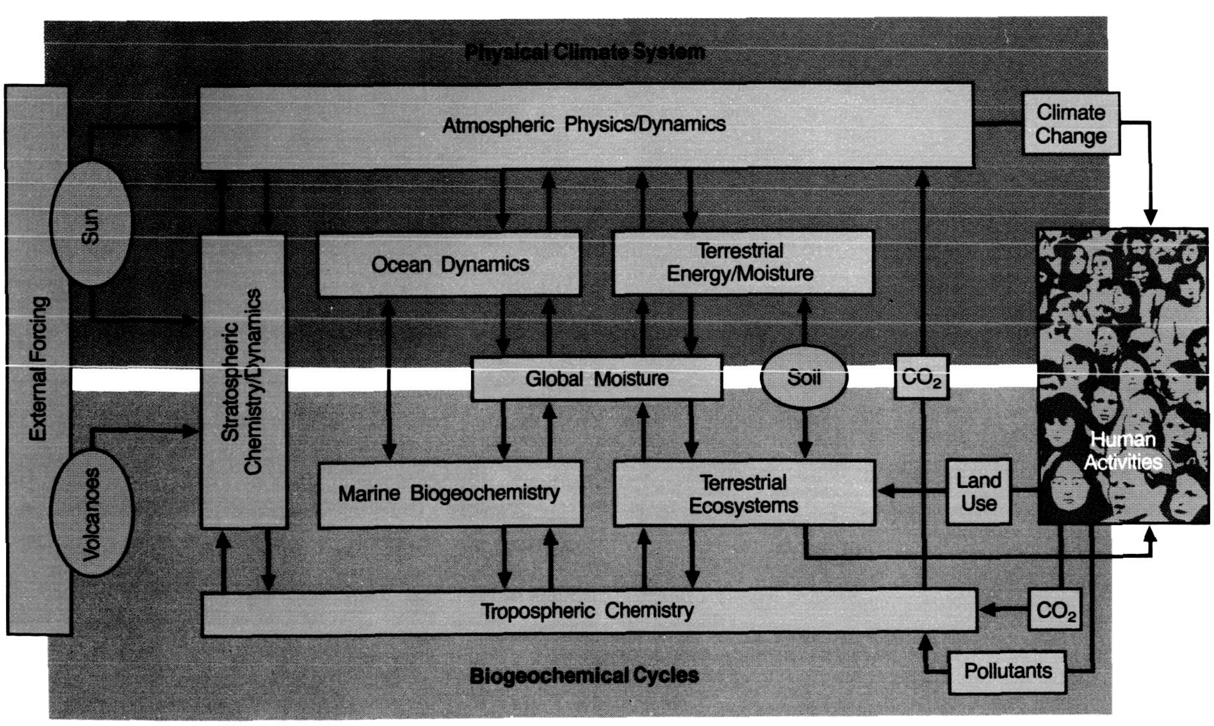
SAN ANDREAS FAULT traces slip zone between the North American and Pacific crustal plates.

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

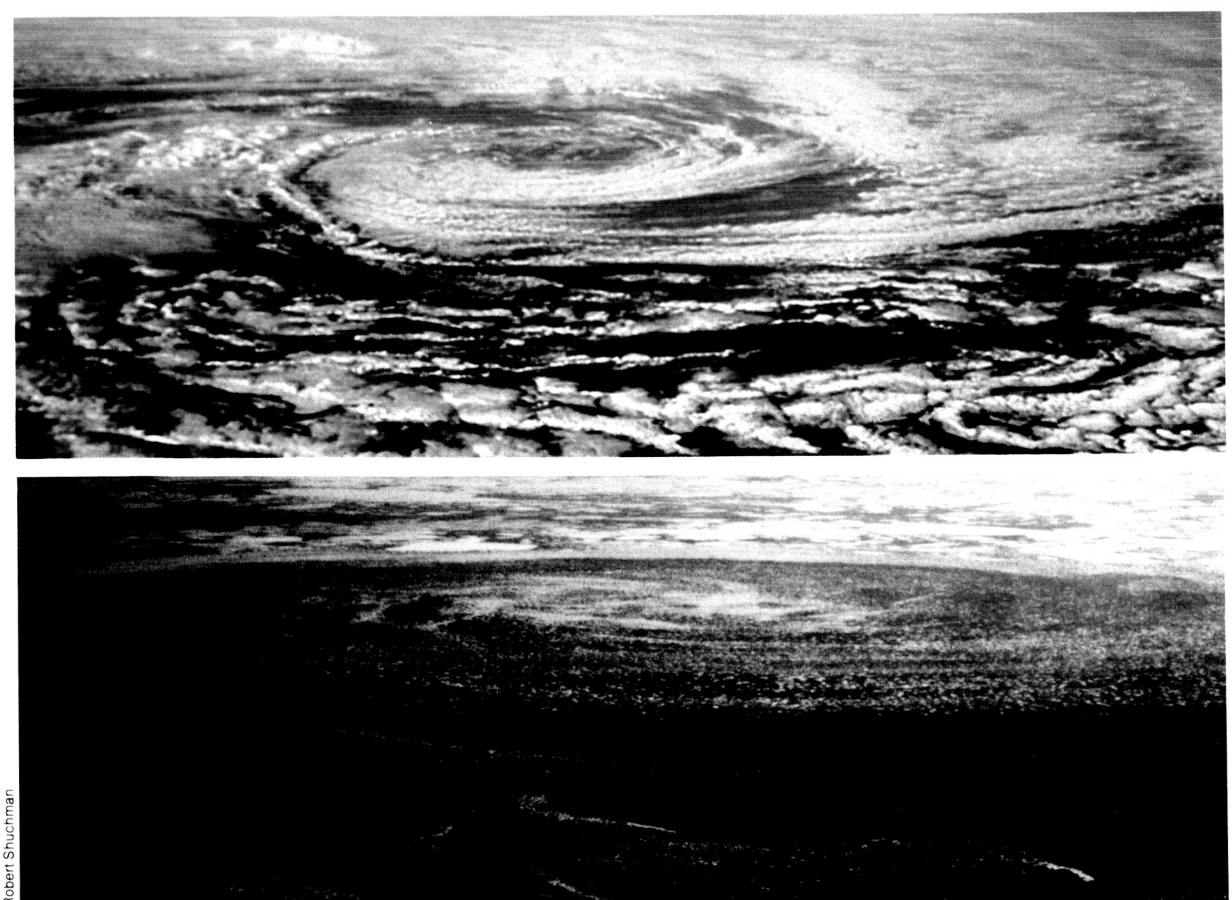
Change on a planetary scale can arise from three causes:

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

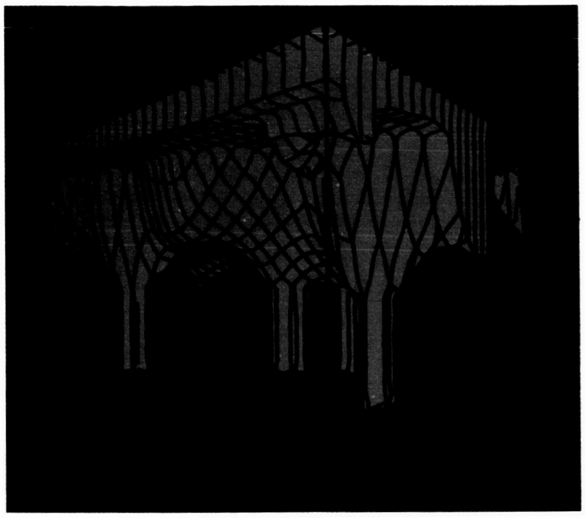
◆ Internal oscillations or instabilities, such as those inherent in the nonlinearity of the system or those introduced by biological evolution, volcanic eruptions, or continental rearrangement; and

◆ Perturbations generated by human activity.

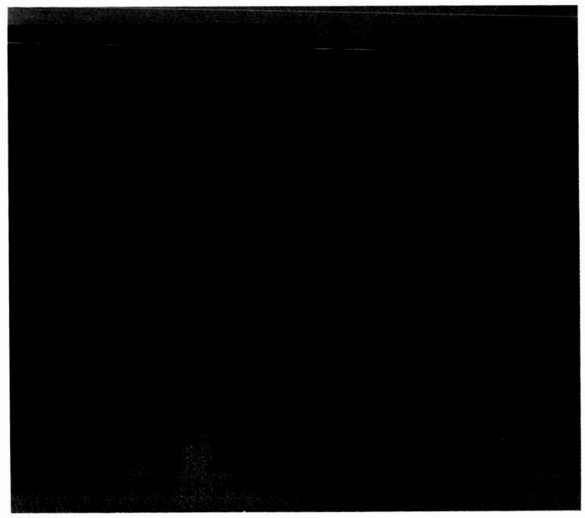
Thus, to describe change on the planet—and hence to distinguish among the changes arising from external, internal, and human-induced effects—we must also carry out observations on a planetary scale. The present description of global change has been assembled from a variety of sources and observations 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-



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.

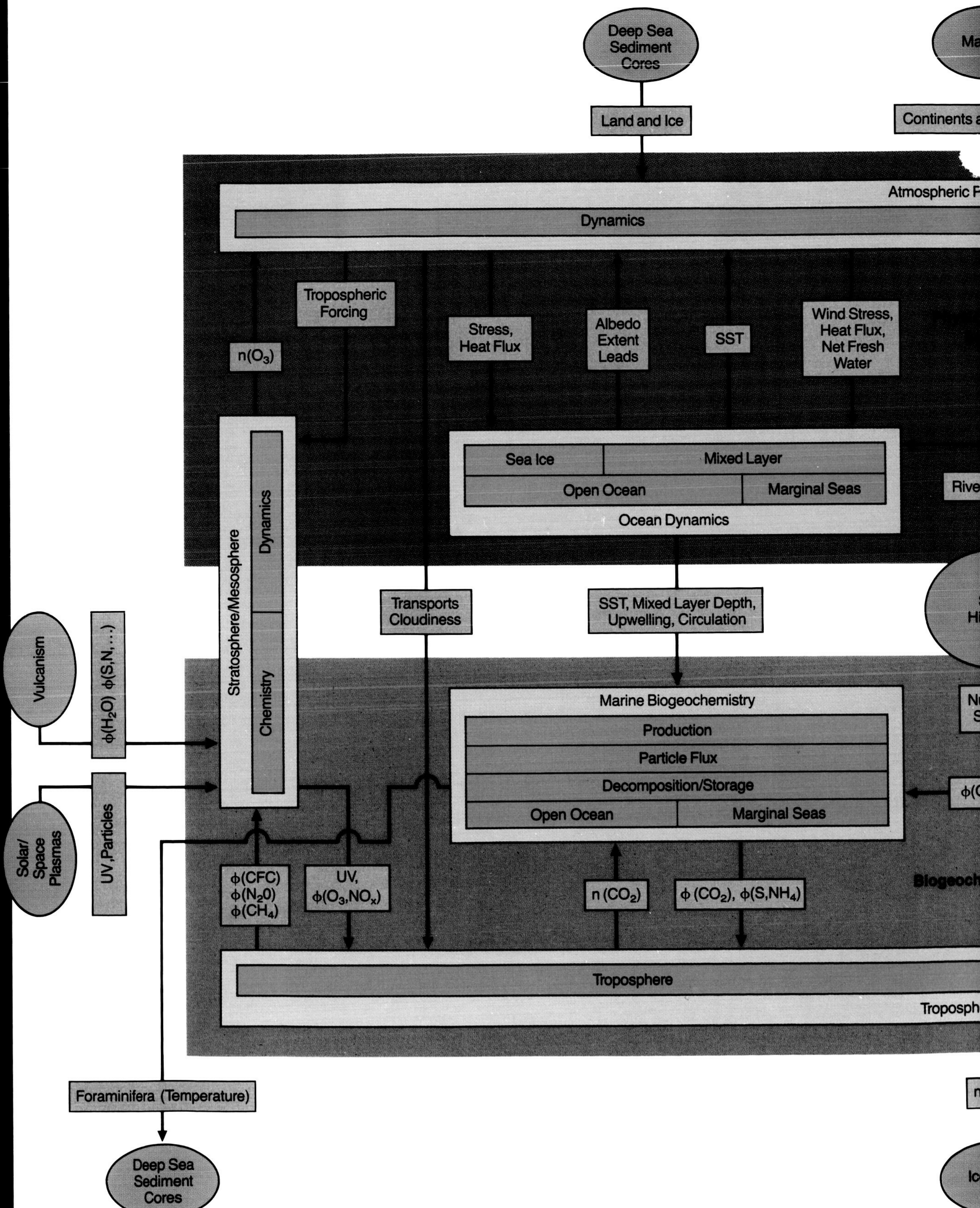
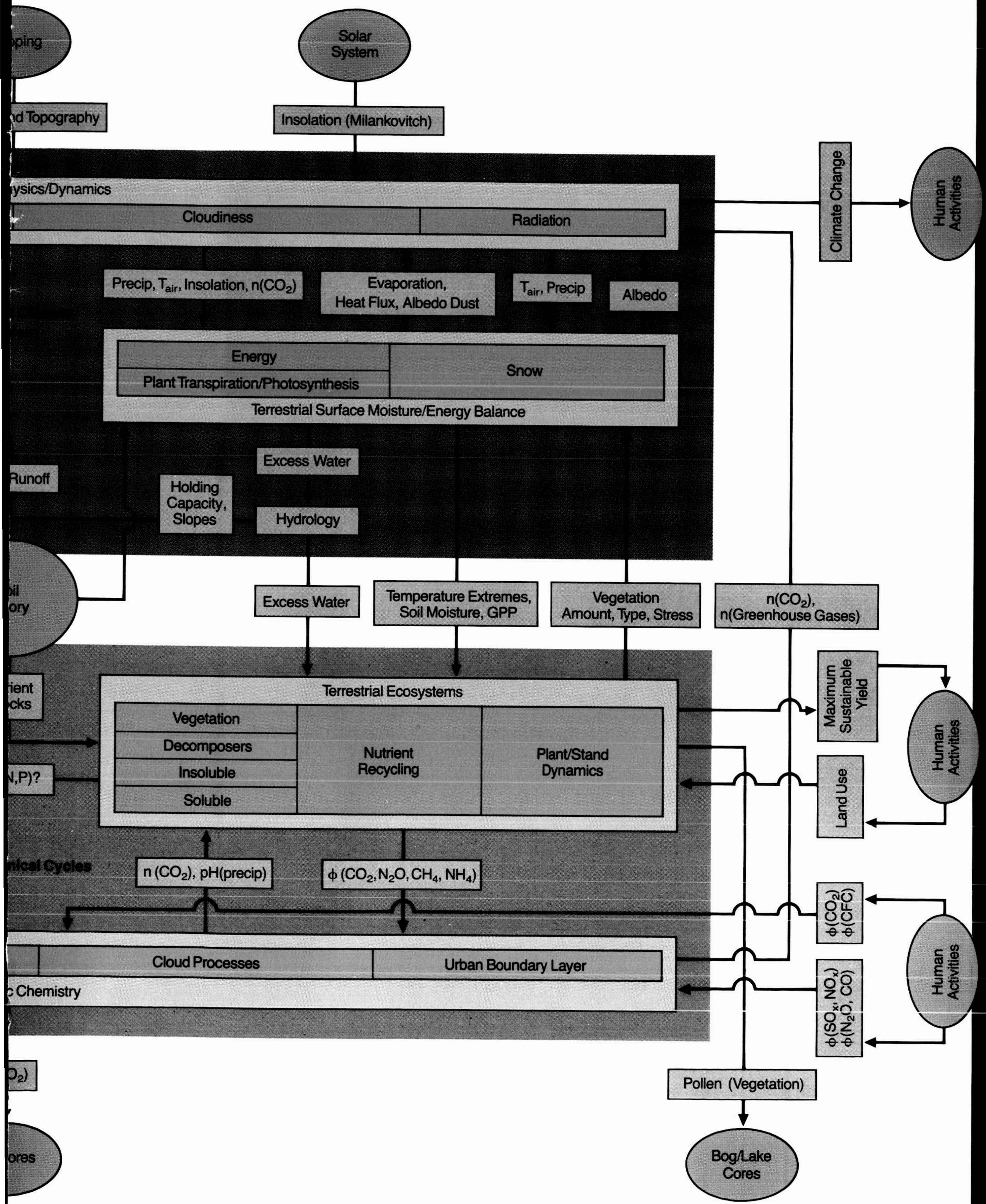


Figure 3. FLUID AND BIOLOGICAL EARTH PROCESSES: DETAILED INFORMATION FLOW
[ϕ(. . .) = flux, n(. . .) = concentration]



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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
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Excess Water
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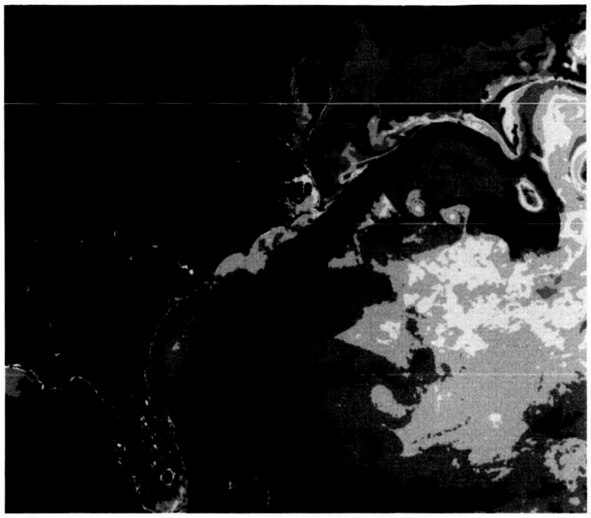
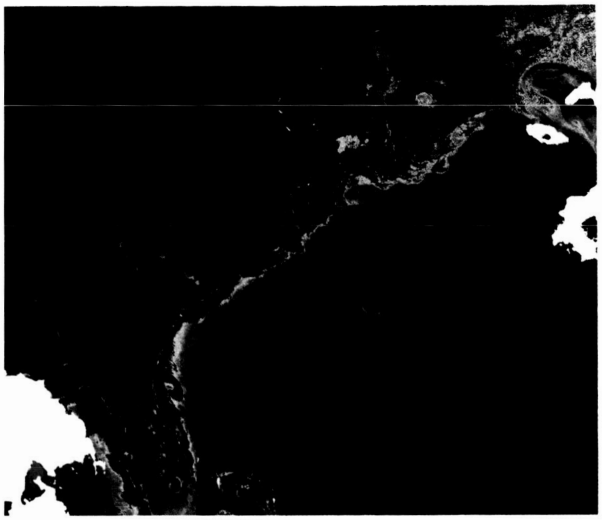




SATELLITE OBSERVATIONS OF SEA SURFACE TEMPERATURE (left) AND OCEAN COLOR (right) demonstrate correlation between marine productivity and physical oceanography. Simultaneous measurements from future satellite systems will expand our knowledge of such processes.

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.

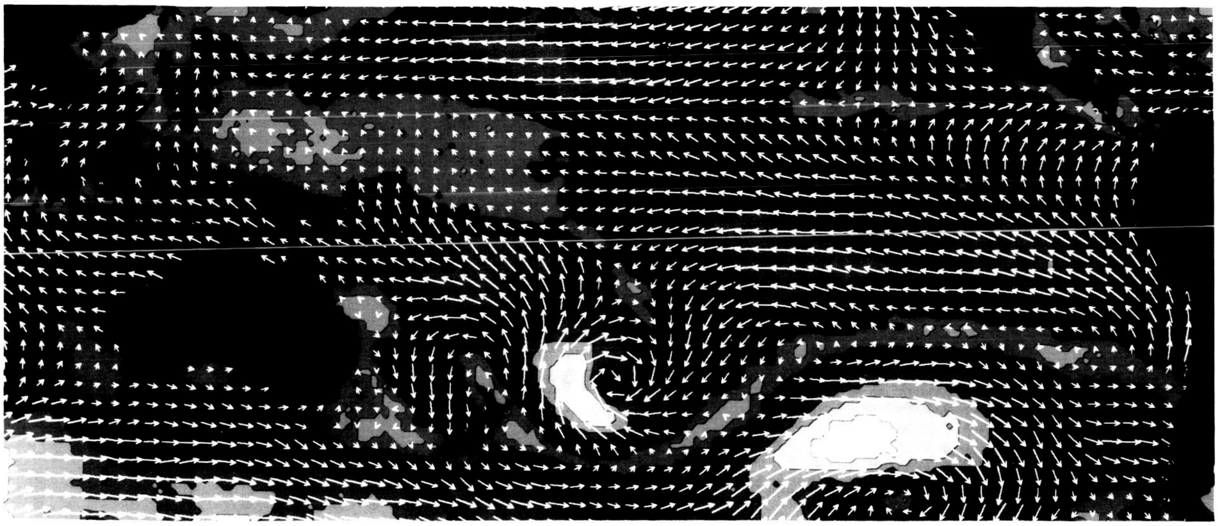
The unique role of space observations in Earth science has been recognized for more than a decade. In order to guide this area of research, the National Academy of Sciences' Space Science Board has provided an overall strategy for Earth science from space through a recent series of committee reports (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.

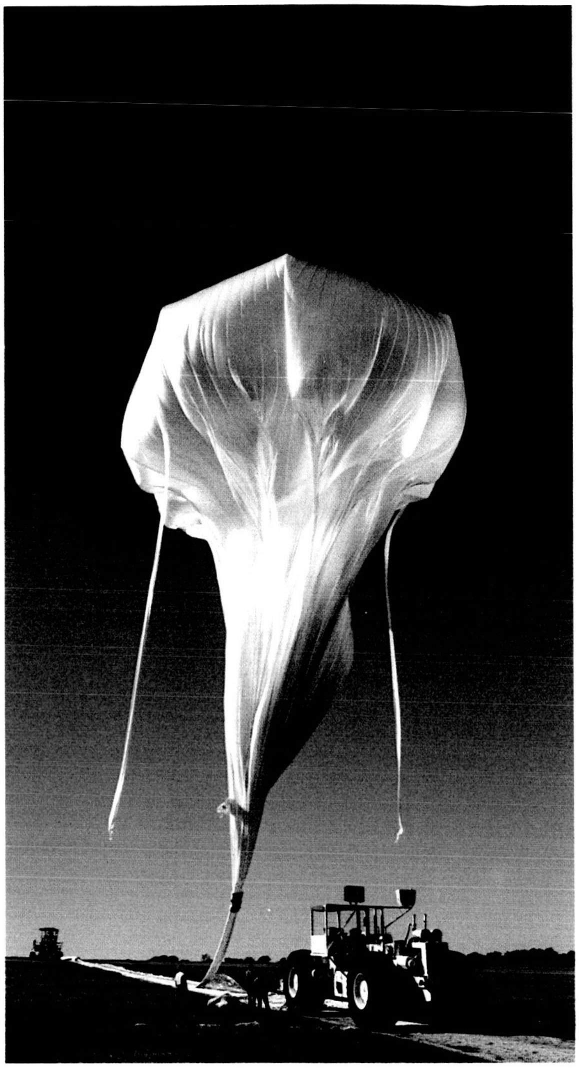
TWO PROGRAM PATHS

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:

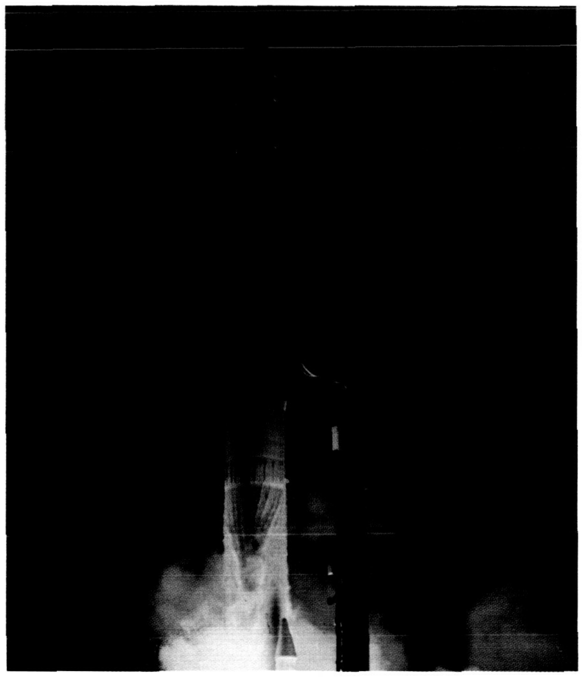
◆ Global moisture content of the atmosphere, and precipitation;
◆ Components of the land-surface energy and moisture budgets;
◆ Biome extent and productivity; and
◆ Winds, especially in the tropics.

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.

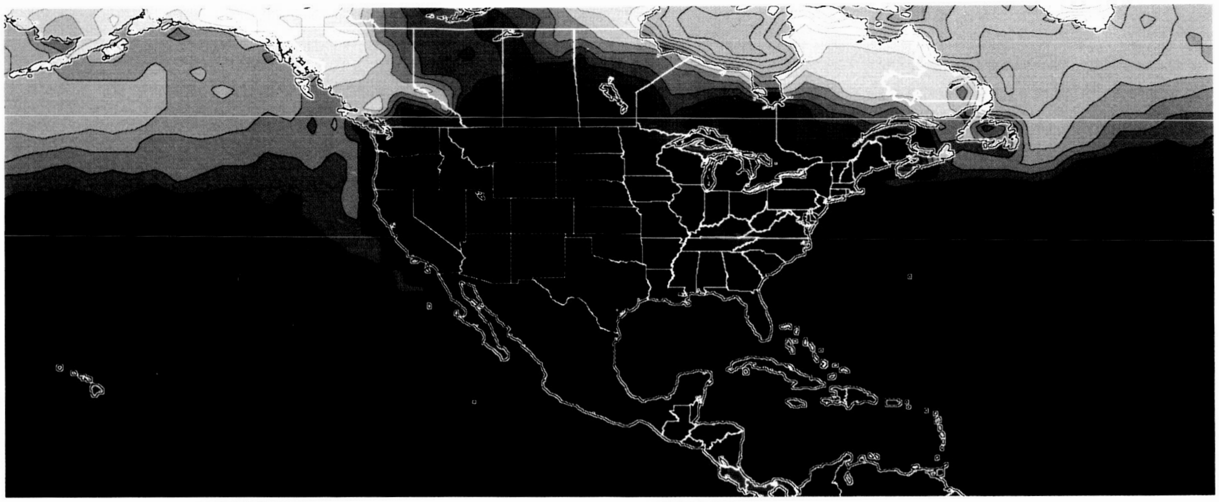
During the second era of research to follow (the mid-1990's and beyond), emphasis will shift to the integrated program of global measurements to be carried out by the proposed Earth Observing System (Eos), as well as NOAA's complement of operational instruments, both of which can utilize new space platforms 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
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

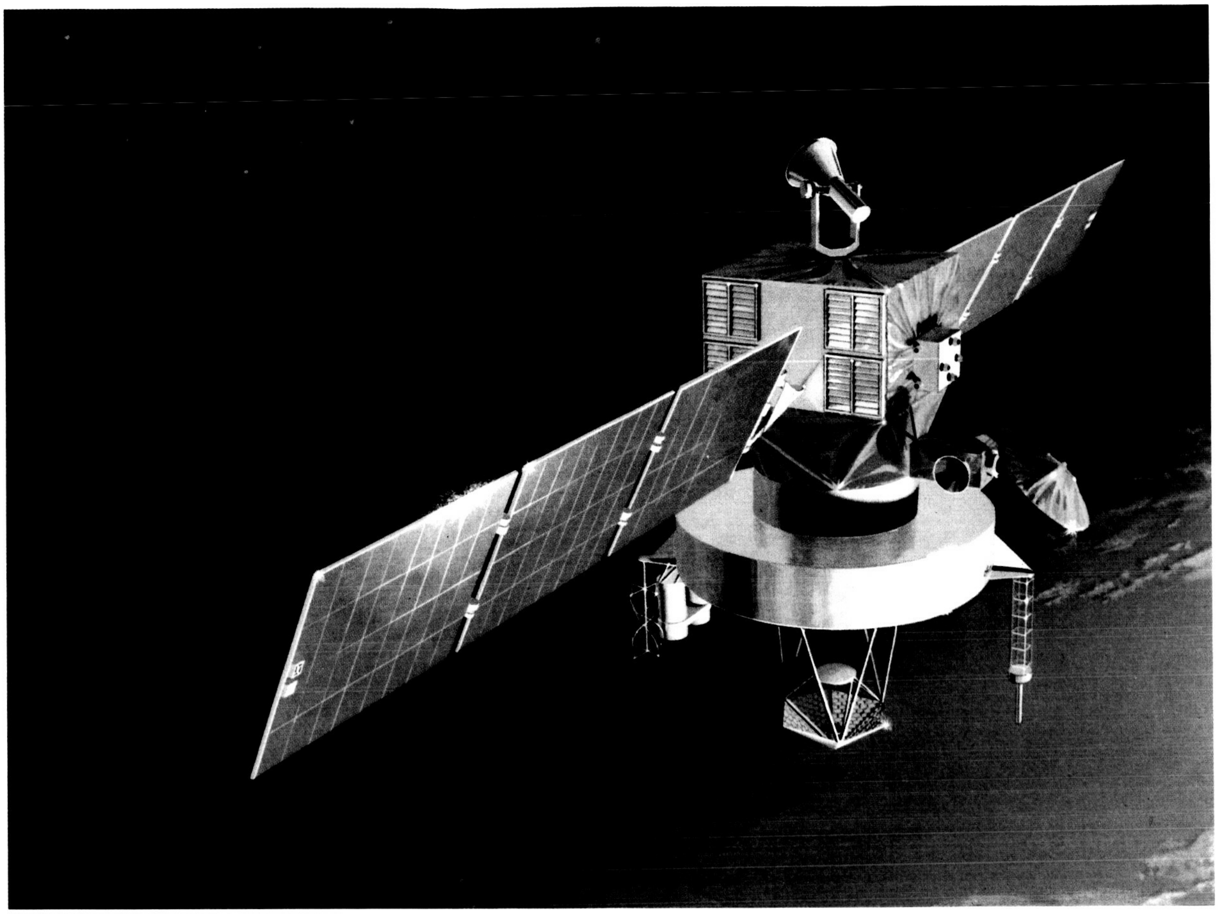
OBSERVATIONAL PROGRAMS FOR GLOBAL DATA ACQUISITION: REPRESENTATIVE EXAMPLES OF PROPOSED FUTURE PROGRAMS

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).

	1985			1990	
United States Space Research Missions	◆ UARS ◆ N-ROSS	◆ TOPEX/POSEIDON		◆ Eos ◆ GRM	◆ Rainfall Mission
Continuing Global Observations	NOAA-8 ➔ NOAA-9 ➔	NOAA-K ➔		NOAA-L ➔	
	GOES-6 ➔ GOES-G ➔ GOES-H	➔		GOES Next (-I,-J,-K)	
	••••• *In Situ* Measurements •••••••••• Land Remote Sensing ••••••••••• Geodesy •••••••• Shuttle Flights •••••••••••••				
Representative International Programs	In Progress: World Climate Research Program: TOGA, ISCCP, ISLSCP Global Environment Monitoring System (GEMS) World Ozone Program Crustal Dynamics Project				

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.

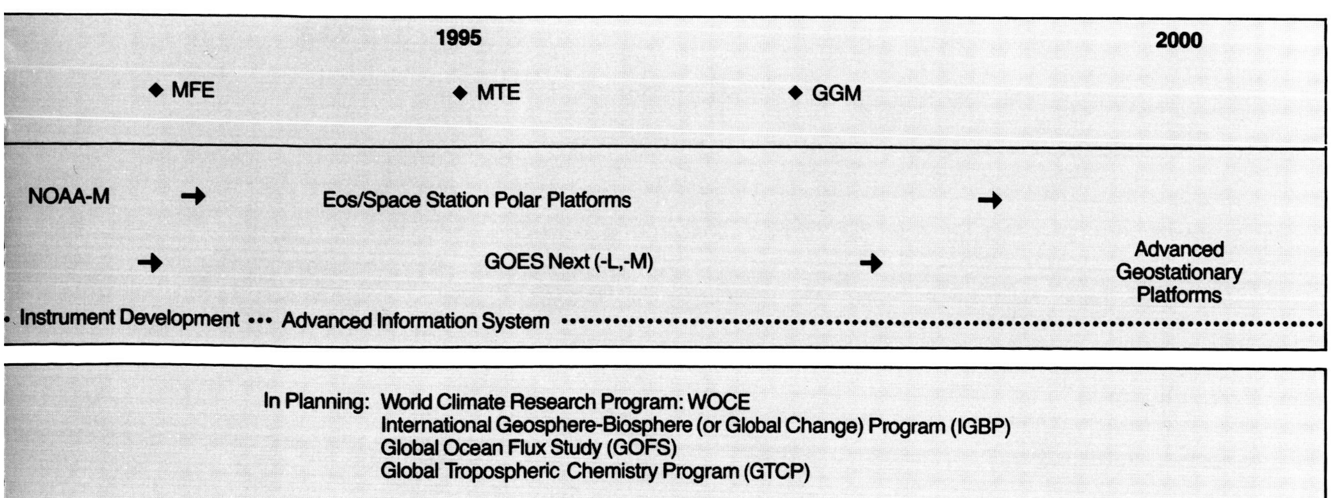
Operational geosynchronous satellites, in service since 1974, have carried imager/sounder instruments providing high-resolution visible and infrared images of the Earth. The infrared channels of the sounding instruments have provided temperature and moisture profiles over large areas of the Earth with 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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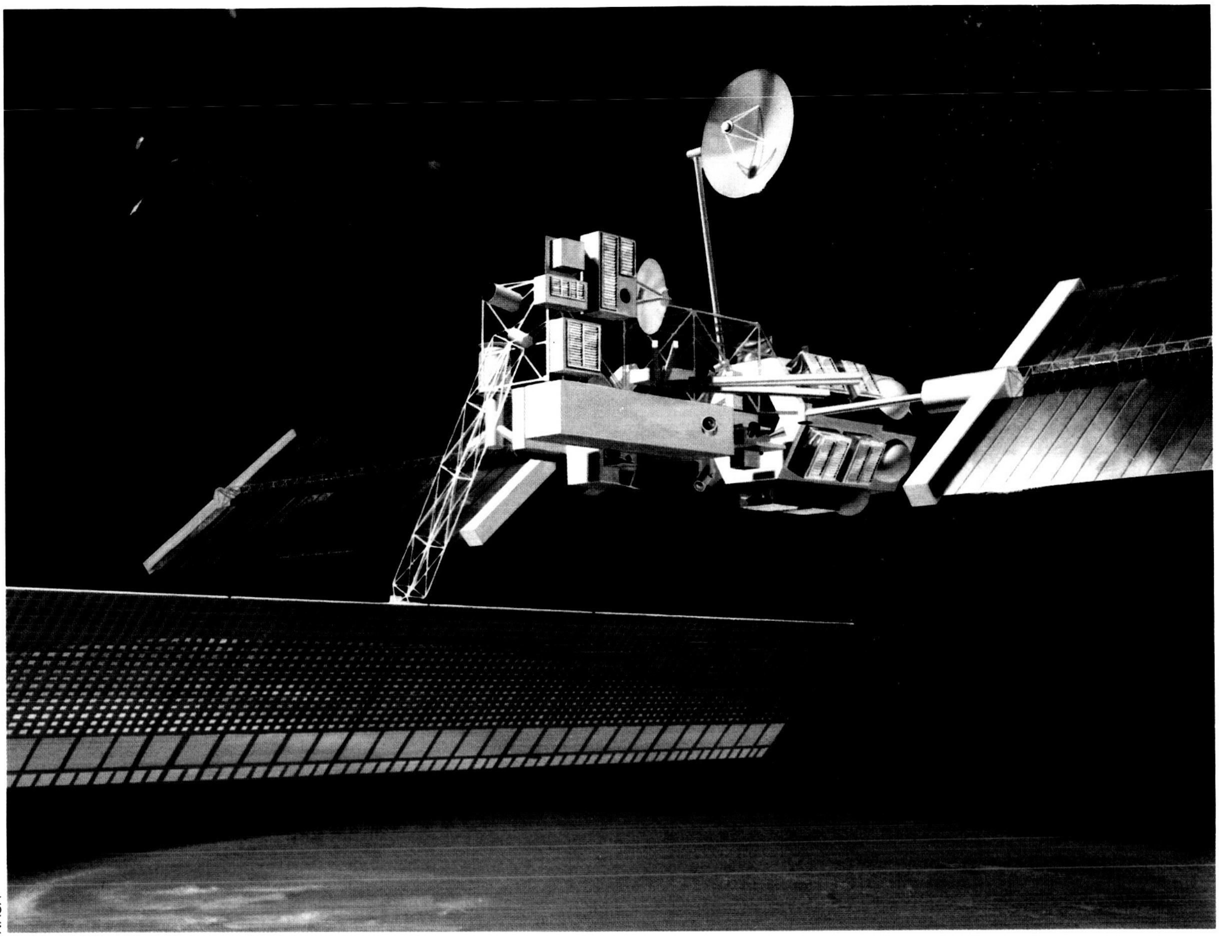
MEASUREMENTS *IN SITU* ARE NECESSARY FOR SUBSURFACE SAMPLING, REGIONAL STUDIES, AND DETAILED INVESTIGATION OF INDIVIDUAL LOCALITIES. Oceanographers study chemical composition of antarctic waters.



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.

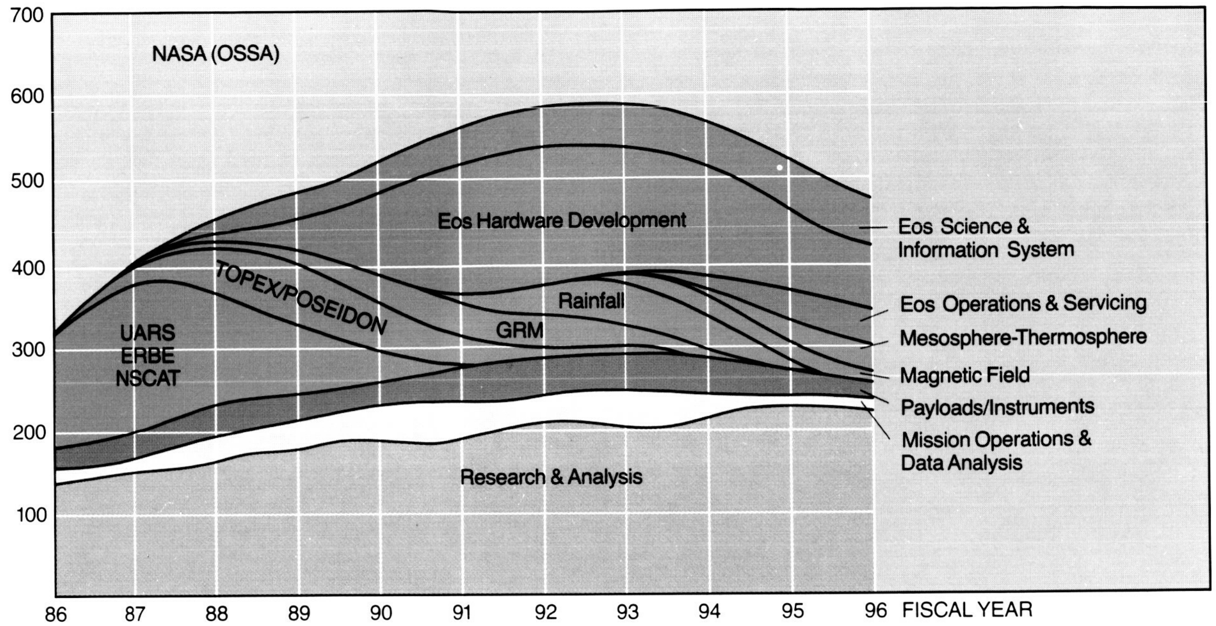


Figure 5. ESSC ESTIMATE OF NASA BUDGET (FY 1986 dollars, in millions).

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

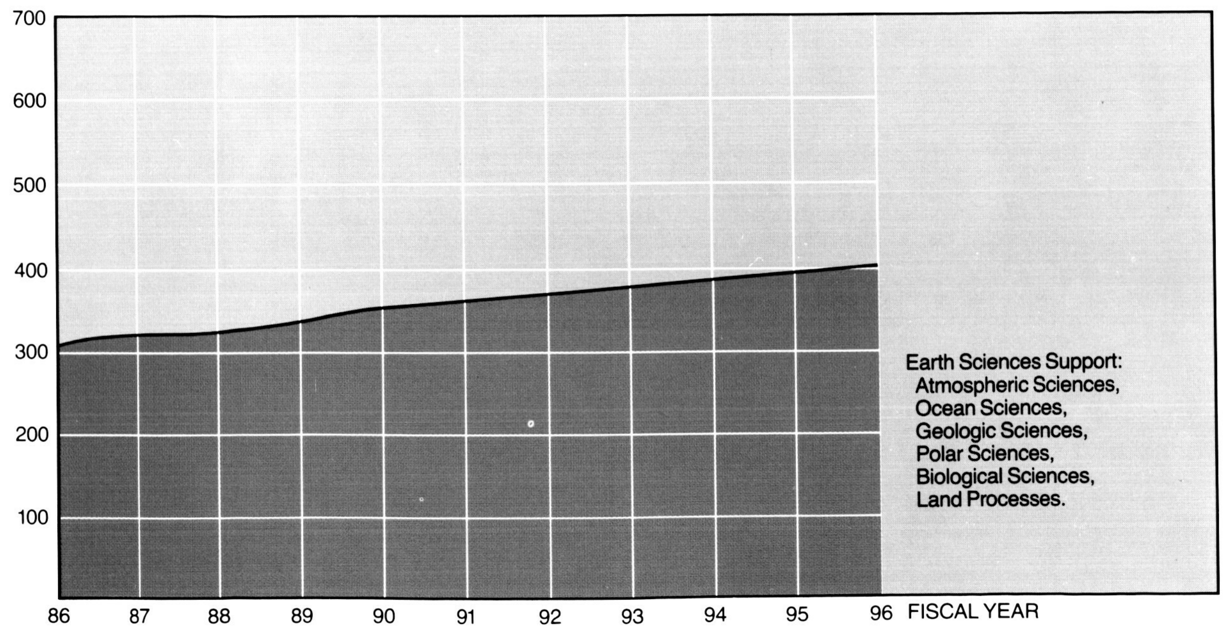


Figure 6. ESSC ESTIMATE OF NSF BUDGET (FY 1986 dollars, in millions).

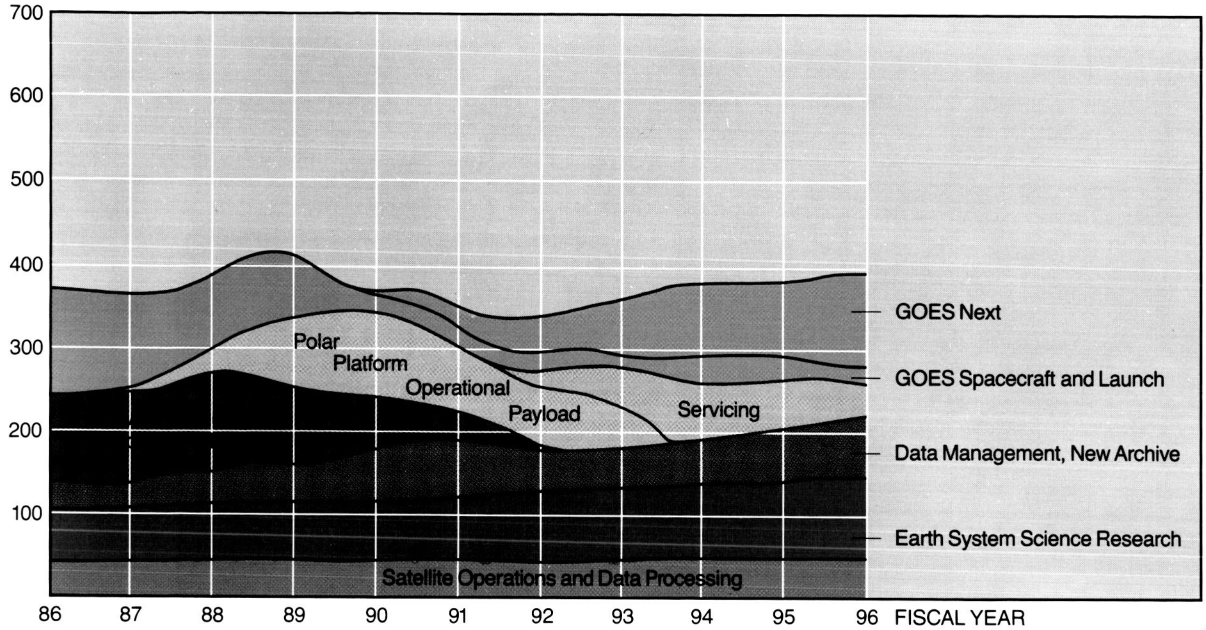


Figure 7. ESSC ESTIMATE OF NOAA BUDGET (FY 1986 dollars, in millions).

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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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.

RESEARCH FOR OUR GLOBAL FUTURE—

◆ **GLOBAL MEASUREMENTS:** Establish worldwide observations necessary to understand the physical, chemical, and biological processes responsible for Earth evolution on all timescales.

◆ **DOCUMENTATION OF GLOBAL CHANGE:** Record those changes that will occur in the Earth System over the coming decades.

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

◆ **INFORMATION BASE:** Assemble the information essential for effective decision-making to respond to the consequences of global change.

We have no greater concern than the future of this planet and the life upon it. Now is the time to meet this challenge through a program of Earth System Science.

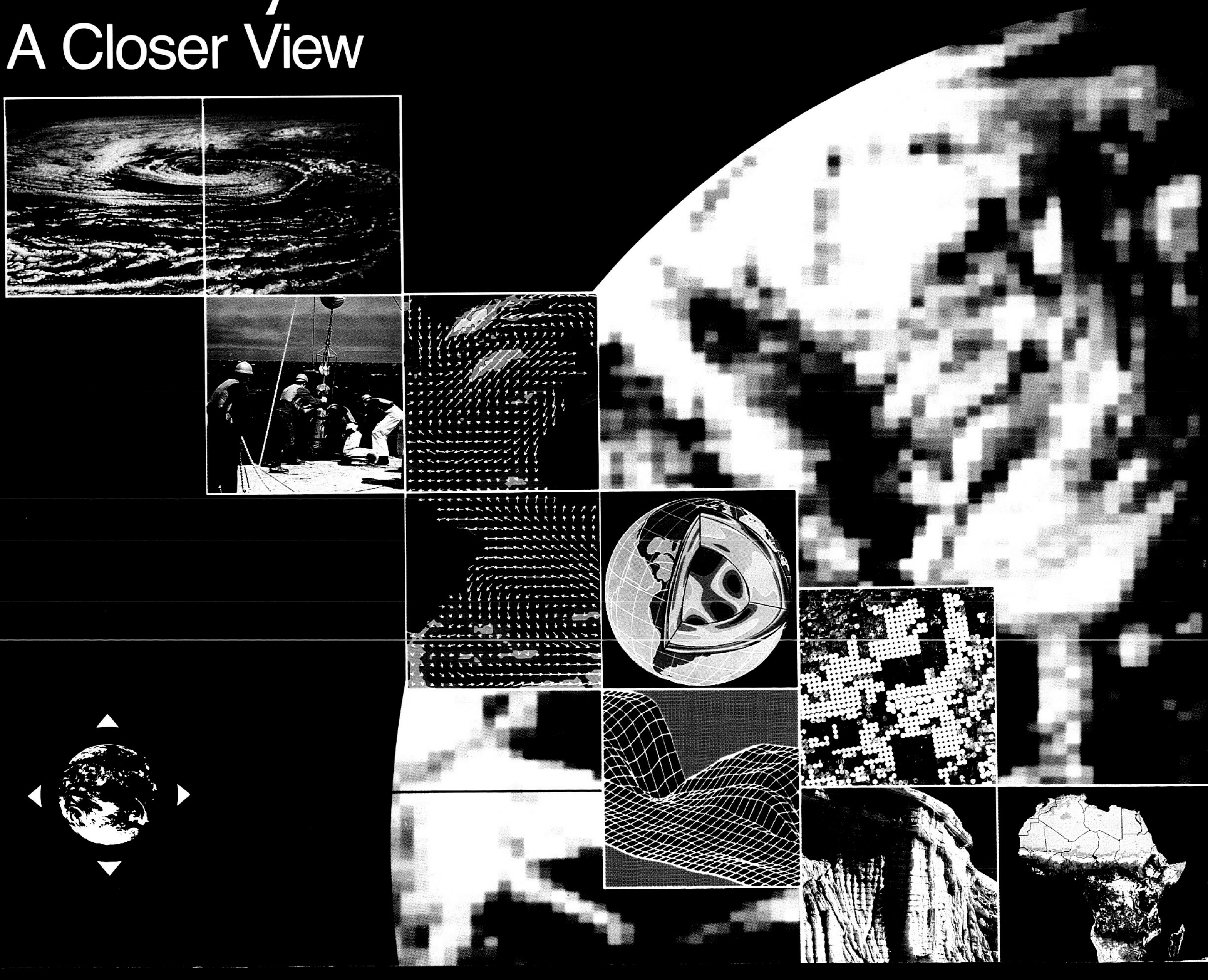
Whatever you can do, or dream you can, begin it. Boldness has genius, power and magic in it.
Begin it now.

Goethe

A PROGRAM FOR GLOBAL CHANGE

Earth System Science

A Closer View



The Goal of Earth System Science

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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.

PREFACE

The Earth System Sciences Committee (ESSC) was appointed in November 1983 by the NASA Advisory Council to consider directions for NASA's Earth-sciences program, with the following charge:

- **Review the science of the Earth as a system of interacting components;**
- **Recommend an implementation strategy for global Earth studies; and**
- **Define NASA's role in such a program.**

We have interpreted this charge as a mandate to define a comprehensive, integrated program to address a scientific research area of great urgency—global change on timescales of decades to centuries—and to identify outstanding opportunities for the contribution of space observations to the study of Earth evolution on all timescales. In view of the broad scope of such a program, the Administrator of NOAA in August 1985 also requested receipt of the ESSC report.

The principal conclusions regarding the central scientific issues and opportunities have been drawn from a number of studies by the National Research Council, notably reports of the Committee on Earth Sciences of the Space Science Board, and of the U.S. Committee for an International Geosphere-Biosphere Programme. These sources have been supplemented by advice from *ad hoc* working groups formed by the committee, whose reports will be published as a supplement to the present report.

Earth System Science

A Closer View

Report of the
Earth System Sciences Committee
NASA Advisory Council

National Aeronautics and Space Administration
Washington, D.C.
January 1988

For further information contact: Office for Interdisciplinary Earth Studies
University Corporation for Atmospheric Research, PO Box 3000, Boulder, CO 80307 USA

PROLOGUE

We are privileged to live in an extraordinary age of scientific research. Scientists around the world 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.

Surely we must do no less to understand the nature of our home, the Earth—to probe its history, to grasp the basic principles of its structure and operation, to gauge the impact of human societies upon it, and to chart its future during the coming decades.

Many of the traditional Earth-science disciplines have reached maturity, bringing new and powerful research tools to bear on the study of the Earth as an integrated system of interacting components. We can now measure directly the inexorable motion of the Earth's crustal plates and their effects upon land topography. Global models of atmospheric circulation have permitted not only routine numerical weather prediction but also investigations of large-scale atmospheric dynamics, thus laying the foundation for climate studies. Three-dimensional models of global ocean circulation, building upon recent insights into the ocean-atmosphere interaction, will shortly be within our reach. Analyses of prehistoric ice layers and ocean sediments are revealing the range of past climatic variations and the cyclic influence of changing Earth-orbital parameters. The decisive importance of global biology in shaping many oceanic and atmospheric properties has also been recognized; forthcoming studies of ocean biota and terrestrial ecosystems will increasingly place these investigations on a firm, quantitative basis. Over the past 20 years, atmospheric chemistry has matured into a vigorous research field, opening our awareness of interactions of the atmosphere with chemical and biological processes in the oceans and on the land surface. All of these activities reflect a consensus of the international scientific community on the importance of understanding the operation of the Earth as a system.

In concert with ground-based research approaches, space techniques have opened up an extraordinarily productive avenue for global Earth observations. Recent advances in technology, ranging from sensor development to advanced computing systems, have given us the means to record and analyze Earth processes with unprecedented completeness and detail. In addition, the documented role of human activities in global change has created the political awareness required for rapid, international steps to respond to this challenge.

The present report of the Earth System Sciences Committee (ESSC) to the NASA Advisory Council is but one of many parallel U.S. efforts to call attention to the need and opportunity for an expanded program of global Earth studies. Others include:

- A 1985 report of the White House Office of Science and Technology Policy, setting out federal agency roles and responsibilities for a U.S. civilian program of Earth remote sensing;

- The 1986 report of the National Commission on Space, which urges, among a variety of important space projects, a long-range global study of Planet Earth;

- An expanding Global Geosciences program within the National Science Foundation, embracing a wide range of Earth-science disciplines; and

- A 1987 report to NASA by the National Research Council's Space Science Board on space science in the 21st century, which also incorporates recommendations for global Earth studies.

The study of the Earth is inherently international. It is therefore significant that U.S. enthusiasm for such study is being matched by many other nations and international coordinating bodies, particularly the International Council of Scientific Unions (ICSU). Numbers of international programs established within recent years have made substantial contributions to research and have demonstrated the productivity of international cooperation. These include the ICSU-sponsored World Climate Research Programme and International Lithosphere Programme, as well as the international Ocean Drilling Program—each of which entails a strong U.S. contribution.

At a September 1986 meeting in Bern, Switzerland, ICSU furthermore endorsed an International Geosphere-Biosphere Programme (IGBP) designed to

"...describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment it provides for life, the changes that are occurring in that system, and the manner by which these changes are influenced by human actions."

Extensive planning for a U.S. contribution to the IGBP has already taken place within the U.S. National Academy of Sciences. It is anticipated that the program recommended in the present report will become an integral part of that contribution.

There has also been considerable interest abroad in U.S. proposals to hold an International Space Year (ISY) in 1992. Understanding of the Earth as a planet is prominent among the preliminary recommendations for ISY scientific programs.

The tragic loss of Space Shuttle *Challenger* in January 1986 has led to serious delays in near-term U.S. space projects. However, if a mixed fleet of launch vehicles is made part of our national space policy, the ESSC recommended program should not be greatly affected by the present hiatus in Shuttle launches, since it is essentially long-range in character.

We have just enough time left in this century to achieve a major new synthesis and understanding of the Earth system. If we succeed, we shall begin the next century with a new view of our home, a prerequisite to perceiving more clearly the overall direction of its future.

Summary of Recommendations

(1) Sustained, long-term measurements of global variables to record the vital signs of the Earth system and the features of global change;

(2) Fundamental description of the Earth and its history to deepen our basic understanding of the planet on which we live;

(3) Research foci and process studies to bring research efforts to bear on key Earth-science problems;

(4) Development of Earth system models to integrate data sets, guide research programs, and simulate future global trends;

(5) An information system for Earth system science to facilitate data reduction, data analysis, and quantitative modeling;

THE NEAR TERM: 1987-1995

◆ **Extension and enhancement of the continuing and operational Earth observations** presently being carried out by the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and others. These programs—including in particular the NOAA series of polar-orbiting and geostationary environmental satellites—are essential to ensure the near-term continuity of long-term measurements of global variables.

◆ **Continued development and timely completion** of a coordinated sequence of specialized space research missions, including the:

- Earth Radiation Budget Experiment (ERBE, launched 1984);
- Laser Geodynamics Satellites (LAGEOS-1, launched 1976, and LAGEOS-2, launch 1993);
- Upper Atmosphere Research Satellite (UARS, launch 1991);
- Ocean Topography Experiment (U.S./France TOPEX/Poseidon, launch1991); and the
- NASA scatterometer (NSCAT) aboard the Navy Remote Ocean Sensing System (N-ROSS) satellite (launch 1992).

These missions extend or initiate key long-term global measurements and are important to a number of near-term process studies.

● **Establishment by NASA of an Earth System Explorer series of research missions,** to be initiated with the Geopotential Research Explorer Mission (GREM, initiate 1989). This series is required for a fundamental description of the Earth and its history on a global scale and for additional process studies.

OBSERVING PROGRAM FOR EARTH SYSTEM SCIENCE: 1995 AND BEYOND

◆ **Initiation of a new era of integrated global observations of the Earth** to meet scientific requirements for sustained, long-term measurements of global variables, a fundamental description of the Earth and its history on a global scale, and process studies. This new era of observations will require:

- An Earth Observing System (Eos) in space, utilizing integrated instrument suites aboard polar-orbiting platforms and providing for three instrument complements—
  - NASA complement (begin instrument studies, 1989),
  - NOAA complement (initiate new instruments, 1989), and
  - Complement furnished by other nations,

  with a NASA new start for Eos in 1990;

- Complementary global research measurements from the ground, aircraft, balloons, and ships;

- Continuation of the series of NASA Earth System Explorer research missions, including the
  - Tropical Rainfall Explorer Mission (TREM, initiate 1991),
  - Magnetic Field Explorer/Magnolia mission (MFE/Magnolia, initiate 1993),

(6) Coordination of federal agencies to ensure effectiveness and efficiency in program implementation; and

(7) International cooperation to further U.S. partnership in a worldwide research effort.

Such a program may logically be implemented during two distinct eras of research opportunities:

- A near-term era, 1987-1995, that includes the flight of currently planned space missions and the conduct of essential process studies; and
- A new era, beginning around 1995, marked by the establishment of a comprehensive observing program for Earth system science employing a new generation of space technology and an integrated suite of ground-based instruments.

◆ **Flight of other demonstrated instruments** on suitable platforms to obtain important Earth system data from space at modest cost. Prime candidate programs include an ocean color scanner, an atmospheric carbon-monoxide monitor, and use of the Space Shuttle for research, instrument development (e.g., scanning radar altimeter), and calibration.

◆ **Expansion and coordination of an interdisciplinary program of basic Earth system research and *in situ* measurements** to be carried out by NASA, NOAA, the National Science Foundation (NSF), the United States Geological Survey (USGS), the Department of Energy (DoE), the Office of Naval Research (ONR), and other federal agencies. Such a program is required for a fundamental description of the Earth and its history on a global scale and for process studies. The basic research supported by the expanding NSF Global Geosciences program, in particular, is a crucial component of U.S. global-change research.

◆ **Development of an information system for Earth system science** to process global data; to facilitate data analysis, data interpretation, and quantitative modeling of Earth system processes by the scientific community; and to lay the basis for further research in the coming decades.

◆ **Development of instruments and techniques** to ready a variety of satellite experiments for implementation in the mid-1990s as part of a comprehensive observing program for Earth system science.

- Mesosphere-Thermosphere Explorer Mission (MTEM, initiate 1995), and the
- Gravity Gradiometer Explorer Mission (GGEM, initiate 1997); and

- Advanced geostationary platforms to support a new generation of research and operational measurements from geosynchronous orbit.

◆ **Expansion and vigorous utilization of the information system for Earth system science.**

◆ **Sustained support by federal agencies for an expanded, coordinated, interdisciplinary program of basic research and process studies.**

BEGINNING AT ONCE

◆ **Development of new management policies and mechanisms** to foster coordination among NASA, NOAA, NSF, and other federal agencies engaged in Earth system science and the study of global change.

◆ **Strengthening of the international agreements and cooperation** necessary for a truly worldwide study of the Earth.

CONTENTS

Earth System Science
A Closer View

Preface .... inside front cover
Prologue 2
Summary of Recommendations 4

1. Research for Our Global Future 10

1.A. Earth System Science:
Emergence of a Global View 12
1.B. The Goal: Understanding
Earth Evolution on All Timescales 13

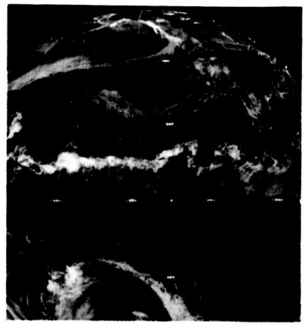
The Earth—A Perspective 14

1.C. The Challenge:
Global Change, Decades to Centuries 16
1.D. A Time to Act 17
1.E. Guide to the Present Report 19
1.F. Scope of This Report 19

Research Briefing by the
National Academy of Sciences 20

Summary and Key Points 21

2. Earth System Science:
A New Approach to Global Change 22



2.A. Historical Perspective 23
2.B. Earth System Processes 24
2.C. How the Earth System Functions:
Conceptual Models 26
2.C.1. Timescales of Thousands to
Millions of Years 26
Conceptual Model: Thousands to
Millions of Years (Foldout) 28
Conceptual Model: Decades
to Centuries (Foldout) 29
2.C.2. Timescales of Decades
to Centuries 30
2.D. Research Approach of
Earth System Science 30

Important Concepts and Terms 32

Summary and Key Points 33

3. Global Change, Thousands to
Millions of Years 34

3.A. Scientific Issues 35
3.A.1. Early-Earth Processes 36

Stromatolites and Their Role in Atmospheric Composition 37

3.A.2. Core and Mantle Processes 38
The Core 38
The Mantle 40
3.A.3. Plate Tectonics 41

Evidence for Plate Tectonics 44

3.A.4. Solar-Driven Processes 46
3.A.5. International Programs and Coordination 47
3.B. Required Observations and Process Studies 48
3.B.1. Plate Motions 50
3.B.2. Plate Deformations 51
3.B.3. Polar Motion and Earth Rotation 51
3.B.4. Time-Dependent Magnetic Field 51
3.B.5. Land-Surface Data 52
3.B.6. Gravity Geoid and Crustal Magnetism 52
3.B.7. Global Seismic Properties 52
3.B.8. Research Foci and Process Studies 53

Summary and Key Points 54

4. Global Change, Decades to Centuries 56

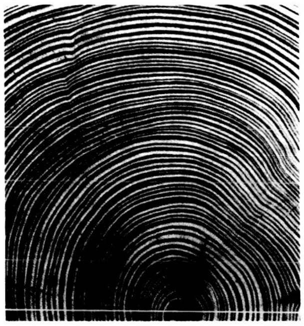
4.A. Scientific Issues 57
4.A.1. The Physical Climate System 57
Atmospheric Physics and Dynamics 59
Ocean Dynamics 61
Terrestrial Surface Moisture/Energy Balance 62
Stratosphere/Mesosphere Dynamics 63

Global Role of Water 64

4.A.2. The Biogeochemical Cycles 66
Marine Biogeochemistry 67
Terrestrial Ecosystems 68
Tropospheric Chemistry 70
Stratosphere/Mesosphere Chemistry 71
4.A.3. System Interactions 73
The Influence of the Biogeochemical Cycles on the Physical Climate System 74
The Influence of the Physical Climate System on the Biogeochemical Cycles 74
The Role of Human Activities 75
4.B. Required Observations and Process Studies 76
4.B.1. External Forcing 78
4.B.2. Radiatively and Chemically Important Trace Species 79
4.B.3. Atmospheric Response Variables 79
4.B.4. Land-Surface Properties 82
4.B.5. Ocean Variables 82

Summary and Key Points 84

5. Paleoclimate: The Link between Long and Short Timescales 86

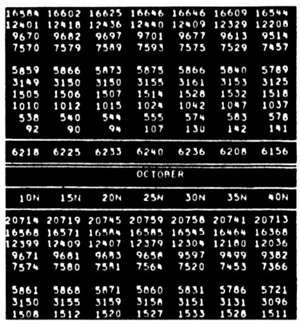


5.A. Scientific Issues and Required Observations 87
5.B. Research Foci and Process Studies 90

The Sun: The Critical Driver 91

Summary and Key Points 93

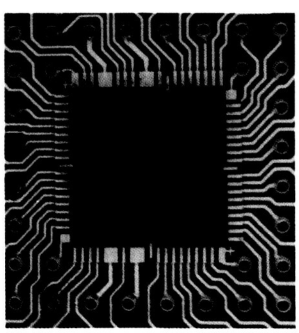
6. Modeling 94



6.A. Formulation of Earth System Models 95
6.B. Tests of Models 96
6.C. Status of Present Models 97
6.D. Model Integration 98
6.E. Feasibility of Predictions 99
6.F. Required Organization and Infrastructure 100

Summary and Key Points 101

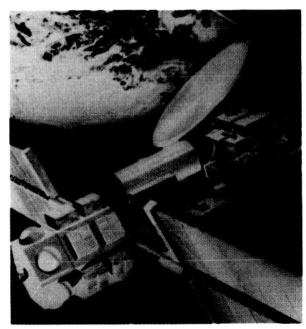
7. Trends in Instrumentation and Technology 102



7.A. Observational Capabilities 103
7.A.1. Instruments for Space Observations 103
Image Analysis versus Global Measurements......................... 103
Instruments for Global Measurements 105
Additional Approaches 107
7.A.2. Systems for Measurements *In Situ* 107
Floats for Ocean-Current Measurements........... 107
Seismic Tomography 108
Advances in Chemical Analyses 110
7.B. Launch Capability and Spacecraft Servicing 112
7.C. Computational Capabilities 113
7.C.1. Supercomputing 113
7.C.2. Advanced Workstations 114
7.C.3. Networking 115

Summary and Key Points 117

8. Observing and Information Systems for Earth System Science: Characteristics and Evolution 118



8.A. Design of an Observing Program for Earth System Science 119
8.A.1. Global Variables versus Process Studies 119
8.A.2. Space versus *In Situ* Approaches 120
8.A.3. Integration in Hardware versus Integration in Software 122
8.A.4. Empirical Data versus Model-Simulated Data 123
8.B. Development of Instruments and Interpretation Techniques...................... 124
8.C. Observing Platforms 126
8.C.1. The Earth Observing System (Eos) ... 126
8.C.2. Earth System Explorer Missions 127
8.C.3. Advanced Geostationary Platforms ... 127
8.C.4. Other Platforms 128
8.D. Measurement System Integrity 128
8.E. Information System for Earth System Science 129

Summary and Key Points 133

9. The Recommended Program 134

9.A. Implementation of the Recommendations 135
9.A.1. The Near Term: 1987-1995 135
9.A.2. Observing Program for Earth System Science: 1995 and Beyond ... 136
9.A.3. Beginning at Once 136
9.A.4. Perspective on the Recommendations 137
Priorities for Implementation 137
Importance of Present Operational Program Base 138
Two-Phase Implementation Timetable 138
Transition to an Observing Program for Earth System Science ... 138
Other Aspects of the Recommended Program 139
Evolution of an Observing Program for Earth System Science ... 139
9.B. Program Components 139
9.B.1. Sustained, Long-Term Measurements of Global Variables ... 139
9.B.2. Fundamental Description of the Earth and its History 141
9.B.3. Research Foci and Process Studies .. 141
9.B.4. Development of Earth System Models 141
9.B.5. Information System for Earth System Science 153
9.B.6. Coordination of Federal Agencies 153
9.B.7. International Cooperation 154
9.C. Federal Agency Roles 157
9.C.1. Role of NASA 158
9.C.2. Role of NOAA 158
9.C.3. Role of NSF 160
9.C.4. Collaboration among NASA, NOAA, and NSF 160
9.C.5. Other Agencies 161
9.D. Recommended Space Missions 161
9.D.1. Continuing and Approved Near-Term Space Research Missions 161
9.D.2. Earth System Explorer Missions 162
9.D.3. Flight of Other Demonstrated Instruments 164
9.D.4. The Earth Observing System (Eos) ... 164
9.D.5. Geostationary Platforms 167
9.D.6. Recommended Space Mission Schedule 167
9.E. Other Issues 167
9.E.1. Commercial Programs 167
9.E.2. NASA Applications 168
9.E.3. NOAA Operations 169

Summary and Key Points 170

Epilogue: Interactions and Education in the Science Communities 172

Photo Essay 173

Appendix A
Observational Programs for Global Data Acquisition 189
Appendix B
Earth Observing System (Eos): Tentative Program Planning 192
Appendix C
A Selection of Recent Reports Relevant to Earth System Science 195
Appendix D
Acronyms, Abbreviations, and Nomenclature 196
Appendix E
Important Concepts and Terms 200
Appendix F
Study Participants 202

Index 204

1

Research for Our Global Future

What is this world on which we live? How did life arise here? What is our future? Among the myriad subjects of human curiosity and endeavor, our Earth—its restless oceans and atmosphere, its shifting layers of rock and ice, and its extraordinary variety of life—has always been a center of our attention.

We have long sought a scientific understanding of the Earth and its various components, and of the laws that govern its structure and evolution. Some of the processes that have shaped the Earth result from relentless geophysical forces acting over millions of years, whereas others reflect the more rapid action of global biology, including human societies. In many cases, the study of these processes has produced practical applications of great benefit to humanity. These have been the two historic motivations for Earth study: an understanding of the Earth as a planet, and the search for practical benefits.

Today a new urgency spurs the quest for knowledge about the Earth. The peoples of the world are no longer passive spectators to the drama of Earth evolution. Through our economic and technological activity, we are contributing to significant global changes on the Earth within the span of a few human generations. We have become part of the Earth system and one of the forces for Earth change, helping to shape an altered environment with poorly understood but potentially serious consequences for our children and grandchildren. The challenge of global change has thus become an additional important motivation for study of the Earth (Figure 1.1).

The demonstrated human role in global change requires that we develop, quite rapidly, a comprehensive program of global Earth studies that transcends the traditional disciplinary boundaries to probe the interactions among the atmosphere, ocean, ice, solid Earth, and biological systems that shape Earth evolution. Such an approach must encompass as well the interactions among processes occurring on quite different timescales which, in combination, have determined the Earth's history and will determine its future. Whether we can or should influence the ways of nature, we must nevertheless strive to understand them—in part to know our Earth better, in part to understand more fully the consequences of our own activities.

Thus we set a new

◆ **Goal:** 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.

And we recognize an immediate new

◆ **Challenge:** 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.

The Earth System Sciences Committee (ESSC) adopts in this report a research approach to address both the goal and the challenge, and recommends a detailed implementation strategy designed to achieve major progress toward both of these objectives within a decade or two. The committee hopes that, in addition, the present recommendations will contribute to the development of a U.S. national program to address global change, within the context of relevant international programs.

In carrying out its mandate, the committee first identified those research areas to which space techniques and observations can make an outstanding contribution. Because of the unique benefits of the space perspective, this identification is key to a broad advance in research on a global scale, and hence to pursuit of the goal. Then, in addressing the more specific issue of global change on timescales of decades to centuries, the committee soon found it necessary to consider also those *in situ* observations required to support and complement the observations from space, and hence necessary to meet the immediate challenge. Because the committee's study focused specifically upon the goal and the challenge, the present report does not attempt to present an implementation strategy for all of Earth science.

The recommendations are addressed primarily to the National Aeronautics and Space Administration (NASA) and, by specific request, to the National Oceanic and Atmospheric Administration (NOAA). Because of the essential role of complementary *in situ* measurements and basic research for the study of global change, the committee is presenting its recommendations to the National Science Foundation (NSF) as well. The ESSC has also considered the roles of these and other U.S. agencies—for example, the U.S. Geological Survey (USGS), the Department of Energy (DoE), and the Office of Naval Research (ONR)—in Earth system science, placing them in the context of national and international efforts directed at global Earth studies.

If pursued with resolve and commitment, the ESSC recommended program will bring us rewards of knowledge as dramatic, and as relevant to human concerns, as any in scientific history. The anticipated achievements of this research program include at least 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 actually occur in the Earth system over the coming decades.

◆ **Predictions:** Use of quantitative models of the Earth system to identify and simulate global trends.

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

The economic, social, and political implications of these anticipated research achievements are not examined in the present report. However, guided by such new knowledge (Figure 1.2), the Earth's human societies may wish to consider, for example: modifications in the use of fossil fuels and mineral resources; political, social, and technical planning for the relocation of primary grain-production areas; controls on the disposal of chemical wastes; or the redistribution of water in response to drought forecasts.

We have no greater concern than the future of this planet and the life upon it. Exploration of the other planets in our solar system has confirmed the very special place of our own 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 the Earth for future human habitation, we must seek a deeper scientific understanding of global Earth processes. Now is the time to meet this challenge through the research approach of Earth system science (Chapter 2) and the ESSC recommended program (Chapter 9).

1.A. EARTH SYSTEM SCIENCE: EMERGENCE OF A GLOBAL VIEW

Most of our knowledge about the Earth has been assembled within historically distinct Earth-science disciplines. Meteorology, for example, has traditionally been concerned with the structure and dynamics of the atmosphere. Plant physiology includes studies of rates of photosynthesis and respiration. Studies of volcanic and sedimentary processes have been carried out within geology, and so on.

Within the past several decades, however, three momentous developments have converged to reveal to us—indeed, to force upon us—a new view of the Earth as an integrated system, whose study must transcend disciplinary boundaries.

The first of these developments is the maturation of many of the disciplines themselves, which has stimulated a recognition of their fundamental connections and interdependencies. Global connections among the Earth's components began to be recognized in the last century. However, it is only relatively recently that scientists in one discipline have had to confront the need for major contributions from other disciplines in order to achieve substantial research advances. For example, continued progress in certain aspects of oceanography now requires a more complete knowledge of the ocean-atmosphere interaction, the influence of polar ice regions, and the distribution and productivity of ocean biota. Key to certain advances in atmospheric science are a better understanding of the role of global biology (including human societies) in the biogeochemical cycles, as well as new insights into the perturbations caused by volcanic eruptions, which can come only from continued research into crustal movements and mantle circulation. A deeper understanding of climate requires knowledge from virtually every Earth-science discipline, including oceanography, atmospheric science, geology and geophysics, and biology.

Second, we now have access to a new

Figure 1.1 EARTH SYSTEM SCIENCE: Three motivations.

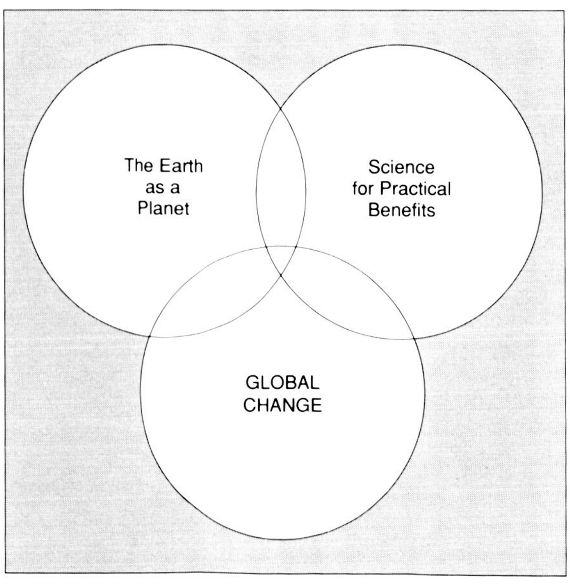
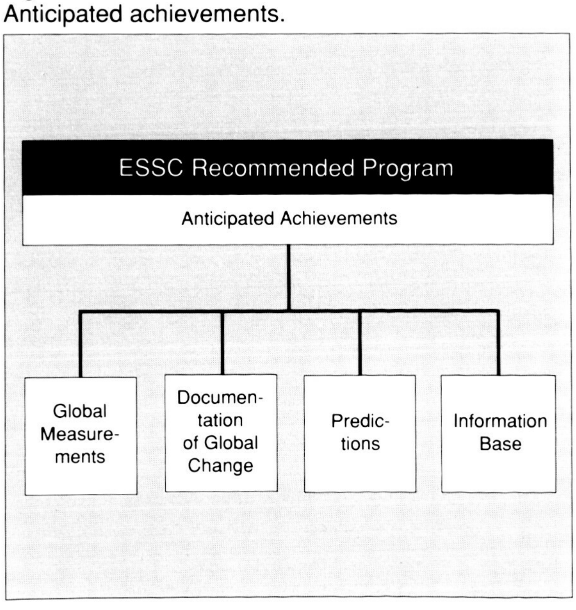


Figure 1.2 ESSC RECOMMENDED PROGRAM: Anticipated achievements.



view of the Earth from space that is both global and synoptic. Space observations have given us, for the first time, the means to survey the many features of our planet both rapidly and efficiently from an inherently global perspective. So powerful and revealing are these satellite investigations that they have become indispensable for future research in the Earth sciences. Moreover, the view of the Earth from space, devoid of the political boundaries that divide nation from nation, has helped to create a new awareness of the common destiny of humanity on this planet—a significant impetus to the international cooperation now required for its study.

Third, the past several decades have brought into sharp focus the increasing role of human activity—demographic, technological, and economic—in the generation of global change. It is one thing to recognize intellectually that, over timecales of millions of years and longer, the Earth is evolving as a result of natural forces beyond our control; it is quite another to face the fact that, over timescales of decades to centuries, we ourselves are now helping to shape the global climate and biology that will be experienced by our descendants. To understand the consequences of our own actions, we must first understand the operation of the Earth system itself.

The maturation of traditional disciplines, a global view of the Earth from space, and the recognition of the human role in global change have combined to stimulate a new approach to Earth studies—Earth system science. In this approach, the Earth system is studied as a related set of interacting processes, rather than as a collection of individual components. In anticipation of deeper insights into the interactions among these components, Earth system science utilizes global observing techniques, together with conceptual and numerical modeling, to investigate both Earth evolution and global change.

Our new view of the Earth system thus corresponds to the intuitive notion that all the components of the Earth must somehow function together. Interactions among the oceans and ice, land masses, the atmosphere, and the biological systems are both significant and complex. The transport of energy and material within and among these subsystems occurs on a global scale across a wide range of timescales. Crucial insights into global change will be obtained not only from studies of present processes but also from an examination of paleoclimate and the geological record, which reveal the changing balances among processes that have shaped the Earth throughout its history.

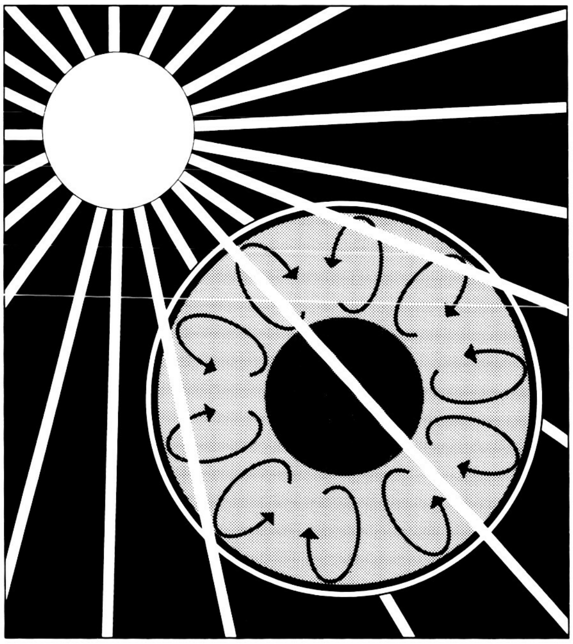
The complexity of the Earth system demands that scientists from a wide variety of specialties work effectively together. The urgency of global change requires new national research priorities and new modes of operation for U.S. agencies—modes that stimulate and maintain new forms and levels of international cooperation. The research approach of Earth system science will touch, to varying degrees, the research interests of all the traditional Earth-science disciplines and will, in time, create new disciplines. Such a development will amplify, rather than diminish, the importance of many specialized research fields and the contributions that they can make to a unified research program. The coming decades thus promise to be unusually productive for the Earth sciences.

1.B. THE GOAL: UNDERSTANDING EARTH EVOLUTION ON ALL TIMESCALES

A deeper understanding of the processes responsible for the evolution of the Earth on all timescales is the ultimate goal of Earth system science.

The Earth can be thought of as consisting of two engines: (1) an internal engine, driven mainly by the radioactivity and primordial heat of the deep interior, which maintains the dynamic plate system creating global topography; and (2) an external, solar-driven engine, which in the long term maintains the weathering and erosion processes that operate above sea level and the deposition processes that operate within the oceans (Figure 1.3).

Figure 1.3 THE EARTH ENGINES: Earth system processes are driven by both internal and external (solar) energy.



THE EARTH—A PERSPECTIVE

The Earth is a planet, a captive of the sun and a mere speck in the universe. Yet it is a very special speck—unique because we live upon it, because we can touch and feel it and can examine its most detailed workings. It is the mirror against which we test our perceptions of things elsewhere—not because we expect them to be the same, but because we seek to understand why they should be different. The rocks and soil, the atmosphere, the ice all have counterparts on other planets. Someday, perhaps, we may find the counterparts of ourselves.

Our Earth can still surprise us with its inherent variability. Only relatively recently have we recognized the Earth to be in continual flux and upheaval on timescales of hundreds of millions of years, the continents in slow but inexorable motion, the oceans opening and closing between them through the force of gigantic convection currents in the underlying mantle. We are no longer astonished to find tropical coal seams in the Arctic or deep ocean trenches just offshore from mountain ranges; however, the specific mechanisms of plate tectonics are only now being thoroughly worked out, together with their implications for the assembly and evolution of the continents, the generation of mineral and petroleum resources, and the origin of hazards to human life, such as earthquakes and volcanic eruptions.

This speck in the universe is also a cradle of life, that remarkable phenomenon that has evolved to marvelous levels of intricacy and specialization amid the seeming disorder and violence of the cosmos at large. The development of life has, in turn, helped to give the Earth its special character. Some three and a half billion years ago, primitive living cells evolved the process of photosynthesis, drawing on energy from the sun to manufacture food and transforming the Earth's atmosphere into one dominated by free oxygen. The subsequent story, which may be read in the fossil record and the rocks in which it is imbedded, is a humbling one. It tells of dinosaurs and of ice ages, of mass extinctions and the emergence of yet other life forms, such as mammals. Biochemistry and molecular biology are now revealing the genetic character of such variation over tens of millions of years. There remain, however, the grand questions of the origin of life, and of the capacity of life processes to adapt to the different environmental conditions that determine its distribution over the Earth.

Now we, the peoples of the world, have become collective participants in these global designs, contributing in barely perceptible but significant ways to the evolution of this special speck in the universe. In our effort to achieve a higher standard of living for an expanding population, we are spreading advanced technology to every region of the Earth and are making steadily increasing demands on natural resources. These actions have begun to alter the atmosphere, oceans, lands, and life forms of our planet in ways that have no precedent in human history. Responsibility therefore dictates that we seek to understand more fully our role upon the Earth and the consequences of global change for humanity. Through the research approach of Earth system science and the program recommended in this report, we can help to ensure that the gifts of the Earth will be preserved and passed on to future generations.

Traditionally, the study of internal processes has been the domain of geology and geophysics, whereas the surface processes influenced by the sun have also been examined within a wide range of other disciplines, including biology, oceanography, and atmospheric science.

There are, however, complex interactions between these internally and externally driven systems, as manifested, for example, by the formation of mountain ranges at lithospheric plate boundaries and the subsequent recycling of sediments arising from erosion. The world's drainage systems—with their associated lakes, aquifers, and soils—also represent a critical interface between the solid Earth and the Earth's atmosphere, hydrosphere, and biosphere. These examples demonstrate the intimate connections between solid-Earth processes and those that operate on the Earth's surface and within the atmosphere.

The broadest view of the Earth as a planet emphasizes the evolution of solid-Earth structure, the formation and chemical composition of the atmosphere and oceans, and the origin of life—all determined by processes operating over millions or billions of years (Figure 1.4). The processes of crustal motion and the oscillations of the ice ages are included here as well. The record of past climate and other variations contained in the Earth's rocks, oceans, and ice sheets is silent and sobering testimony to the brevity of human experience within the span of geological history.

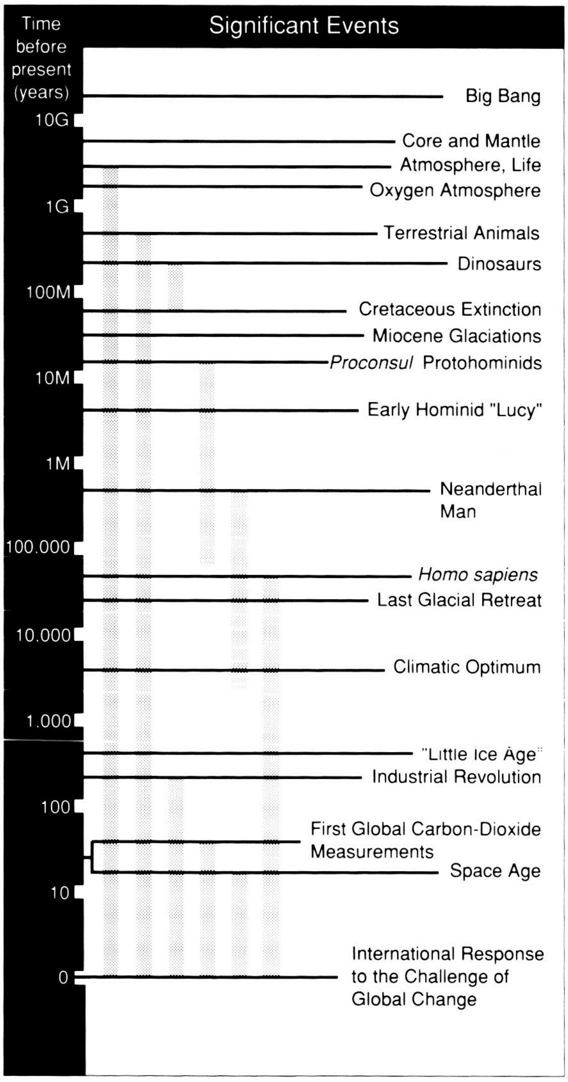
Intermediate timescales—decades to centuries—present an intriguing and urgent challenge. It is over these timescales that natural change has major effects on humanity, and that the effects of human activity on global processes are most pronounced. Central themes at this temporal scale are the physical climate system and its interaction with living organisms and the biogeochemical cycles—particularly the recycling of nutrients, the maintenance of those trace gases in the atmosphere that affect climate, and the role of temperature and moisture in determining the distribution of life over the Earth.

Processes that occur on even shorter timescales can contribute to Earth evolution as well. The local and constantly changing fluxes of energy, momentum, and matter in the atmosphere and ocean, and the influence of these fluxes on the land surface and on vegetation, can sum over days, months, seasons, and years to produce alterations in both climate and global biogeochemistry. The somewhat irregular, multiannual oscillations in atmospheric and oceanic motions and thermal structure produced in response to such flux changes can contribute to Earth evolution on even longer timescales.

Moreover, the inherent nonlinearity of the equations governing the components of the Earth system ensures that change in any one component and time regime is eventually distributed to other components, often manifested at different timescales. For example, an approximately centennial repetition of seismic-energy release in a given segment of a plate boundary gives rise to earthquakes on timescales of seconds. Conversely, the effects of volcanic 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. Both earthquakes and volcanism are manifestations of some of the longest-term processes in the Earth system, yet their devastating effects can impinge violently on the shortest-term operations of terrestrial ecosystems.

It is thus clear that any attempt to understand Earth evolution must incorporate the

Figure 1.4 EARTH EVOLUTION.



study of a wide variety of Earth processes operating at virtually all timescales, and must consequently draw upon all of the major Earth-science disciplines for guidance and information. The program recommended in Chapter 9 of this report represents a major step in this direction.

1.C. THE CHALLENGE: GLOBAL CHANGE, DECADES TO CENTURIES

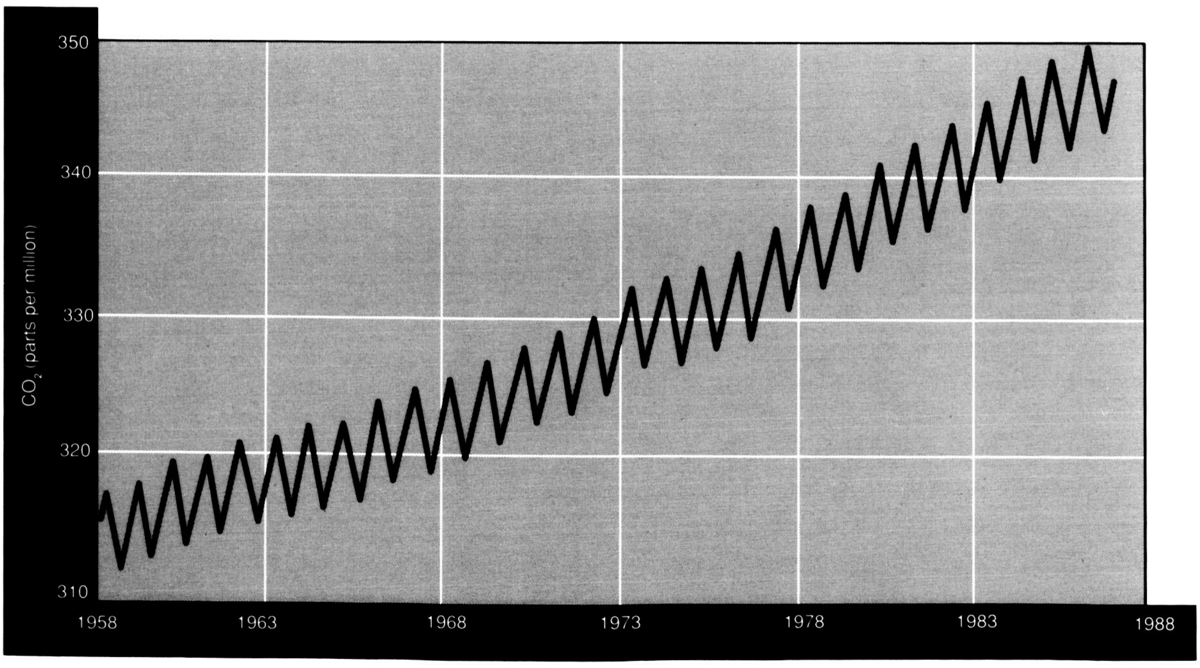
The understanding of global change on timescales of decades to centuries is a challenge of great urgency. Accordingly, the Earth System Sciences Committee believes that meeting this challenge—while maintaining an overall perspective of change on all timescales—should be given highest priority within the recommended program.

As our home, the Earth is our source of food, shelter, and materials. During the brief time human beings have been here, we have learned to insulate ourselves from some of its extremes and to exploit the Earth for our benefit. Our agricultural system supports an ever-growing population. Our industrial technology draws heavily on mineral resources throughout the crust of the Earth. We have explored the land surface, the ice caps, and the ocean depths. We have learned to navigate the seas, to survive in the Antarctic, to fly in the atmosphere, and to observe the Earth from space. Underlying all of our scientific and technical endeavors on the Earth is the hope that they will, additionally, furnish our children and grandchildren the opportunity for a better life.

Scientific and technological advances notwithstanding, our global environment—the climate, the soils, and the other life around us—is an integral part of our existence, and we must come to terms with the constraints it imposes. We now know that we are changing our global environment in fundamental but poorly perceived ways through our industrial activity and land-use practices. Simple extrapolation from past experience is no longer reliable. Because of short-term natural fluctuations, many of the resulting trends will remain undetected until they are effectively irreversible. Some of the consequences may benefit individual communities or the whole of humanity; others may not. While well-planned adaptation may well be constructive, adaptation in a crisis will almost certainly be painful.

For example, the burning of oil and coal is injecting carbon dioxide into the atmosphere at unprecedented and accelerating rates, an effect that is believed to be largely responsible for the steadily increasing atmospheric concentration of this gas worldwide (Figure 1.5). Carbon dioxide in the atmosphere acts like the glass in a greenhouse, permitting incoming solar radiation to reach the surface of the Earth unhindered but restricting the outward flow of infrared radiation, thus producing a net warming of the surface (Figure 1.6). Some of the injected carbon dioxide is absorbed by the oceans, and changes in land vegetation may also affect the balance; how-

Figure 1.5 OBSERVED INCREASE IN ATMOSPHERIC CARBON DIOXIDE, resulting largely from human activities.

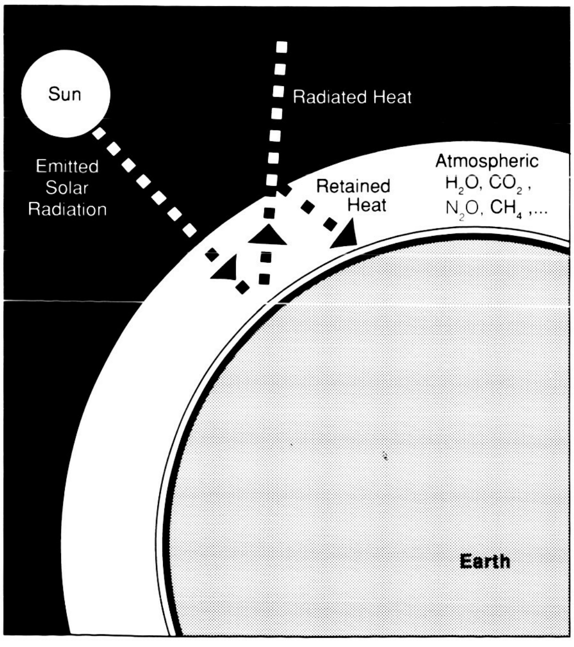


ever, from the trend observed, it seems inevitable that atmospheric carbon dioxide will at least double in the next 50-100 years. On the basis of this scenario, our most comprehensive climate models predict a rise of some 2 °C in global average surface temperature—comparable to that which has already occurred in the 18,000 years since the last ice age, but unprecedented in recent history. These models also predict still greater temperature increases at high latitudes, together with substantial shifts in worldwide precipitation patterns.

Time histories of pollen from lakes and of plankton skeletons from ocean sediments show that climate changes of this magnitude are associated with major shifts in vegetation patterns on land and species distribution in the ocean. The feedback of biological processes to climate change remains largely unexplored, but it is thought to be substantial.

There are other disquieting signs of global change produced by human activity. Large-scale damage to terrestrial ecosystems from acid rain is increasing around the world. Chlorofluoromethanes (CFMs) of industrial origin have accumulated sufficiently to influence the chemical processes of the ozone layer in the stratosphere. Atmospheric methane is increasing particularly rapidly, for reasons that are not yet clear; both increased agricultural productivity and urban air pollution may play important roles. Methane, CFMs, and other chlorofluorocarbons are examples of a whole class of "greenhouse gases" which, although individually of less significance than carbon dioxide, collectively may be expected to produce an effect of similar magnitude.

Figure 1.6 THE GREENHOUSE EFFECT: Atmospheric gases opaque to infrared radiation create a global warming trend.



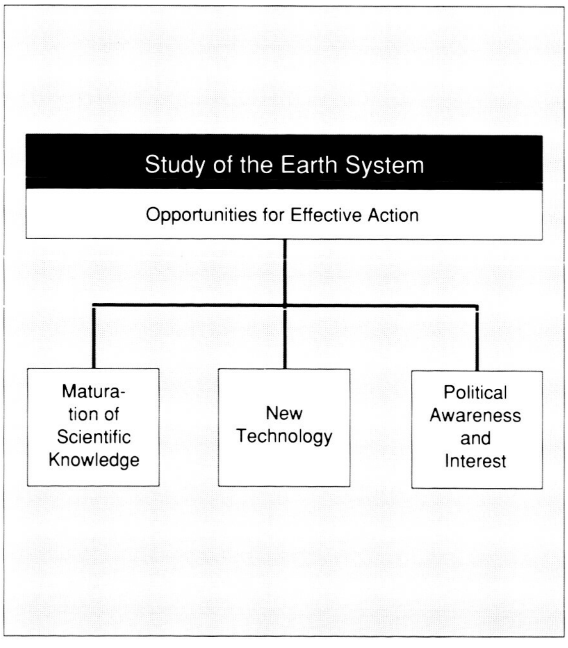
1.D. A TIME TO ACT

The foregoing discussion demonstrates the reality of global change over the span of a human lifetime. We cannot yet predict the boundaries of the changes we have set in motion. However, these human-induced changes in the Earth system provide an opportunity as well as a challenge. These changes are data on the characteristic dynamics of the planet. It is as if humankind were tapping the Earth's drum; now, by listening carefully to its changing rhythms and sounds, we will be better able to determine the shape and structure of the drum itself.

The initiation of a comprehensive program to investigate the complex interactions within the Earth system could not be attempted without the research base provided by traditional disciplinary investigations and the advanced technology now available. The increasing evidence of direct human influence on global Earth system processes implies that we dare not risk delay. The following opportunities for effective action demonstrate that now is the time to act:

◆ **Maturation of scientific knowledge** of the Earth system and its components has revealed the questions that will guide future

Figure 1.7 STUDY OF THE EARTH SYSTEM: Opportunities for effective action.



research, permitting us to integrate the efforts of many traditional disciplines in the study of the Earth as a global system.

◆ **New technology** can yield the necessary global observations from space and from the Earth's surface, and can provide the computational capability needed to process, analyze, and interpret these observations.

◆ **Heightened political awareness and interest** has focused worldwide attention on the importance of global change to our environment—in particular, on the role of human activity in this process—and has created an international political consensus for action.

As a consequence of these opportunities, new program initiatives within federal agencies concerned with Earth studies are becoming increasingly complementary and are converging toward a unified, coherent approach to an investigation of the Earth as a system.

The momentum now gathered for a unified study of the Earth system (Figure 1.7) cannot be allowed to dissipate. Earth system science is inherently an international endeavor; the Earth System Sciences Committee therefore believes it imperative for the United States to continue its commitment to and partnership in such research, in concert with the other nations of the world. U.S. federal agencies will thus need to take a series of decisive actions in the near future.

The National Aeronautics and Space Administration (NASA) will need to:

- Make the long-term commitment to Earth system science necessary to ensure that the nation's most advanced technological capabilities are marshalled to obtain and utilize required new global observations of the Earth that can only be obtained from space;

- Fund the research and technological development required to carry out such global observing programs;

- Implement space missions aimed at resolving important questions and issues in Earth system science;

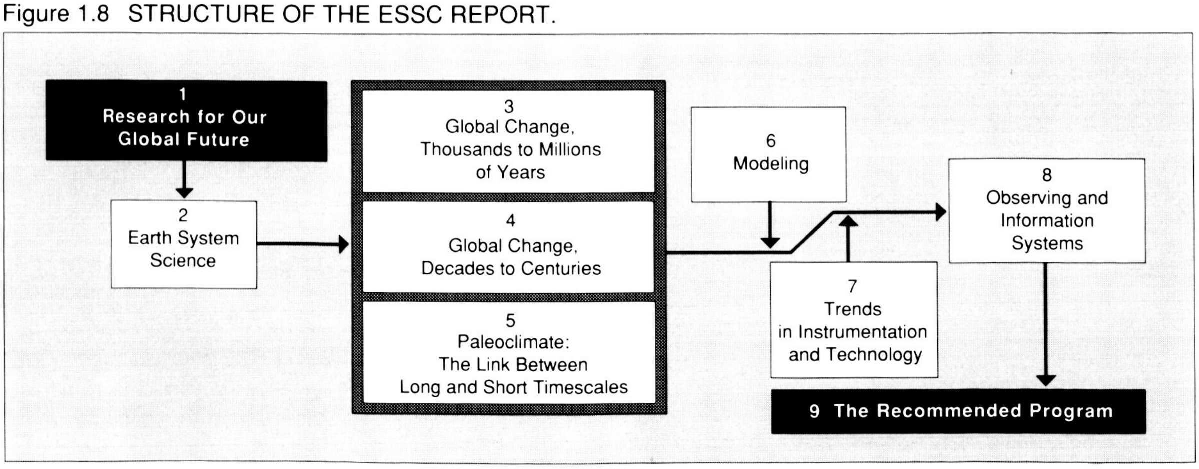
- Sustain the scientific research and the information system that will be necessary to transform global data into scientific knowledge of the Earth system; and

- Disseminate to other agencies those observational and data-management capabilities that prove to be effective and necessary for the long-term observational program required to document global change.

The program of the National Oceanic and Atmospheric Administration (NOAA) must be broadened beyond its present scope in order to meet the needs of Earth system science. NOAA will need to make a long-term commitment to fostering this research field by continuing its series of long-term global measurements, by facilitating the research use of its operational data (both from the Earth's surface and from space), and by responding to research needs in the implementation of new observing systems.

The expanding Global Geosciences program of the National Science Foundation (NSF) is an exciting and highly important component of U.S. global-change research. In addition to maintaining its traditional role of supporting basic research in the Earth sciences, NSF must continue to foster interdisciplinary programs and to place an emphasis on those aspects of particular importance to understanding and modeling the Earth as a system. Many other federal agencies concerned with Earth studies—such as the U.S. Geologi-

Figure 1.8 STRUCTURE OF THE ESSC REPORT.



cal Survey (USGS), the Department of Energy (DoE), and the Office of Naval Research (ONR)—must also take timely steps toward participation in this national and international effort.

1.E. GUIDE TO THE PRESENT REPORT

The overall report structure is depicted schematically in Figure 1.8. Following a historical perspective, Chapter 2 introduces two of the fundamental features of Earth system science: a view of the Earth system as a set of interacting processes, and the conceptual Earth system models that permit these processes and their interactions to be studied quantitatively. There follows an outline of the research approach of Earth system science, in which the acquisition of observations, analysis and interpretation, modeling, and verification and prediction are cyclically related.

Chapters 3, 4, and 5 summarize the primary scientific questions and issues relating to global change, as well as the observations and process studies required for research progress. The important role of space observations is emphasized, together with the *in situ* observations needed for a complete understanding of Earth system interactions. Chapter 3 presents detailed discussions of processes operating on timescales of thousands to millions of years and longer, which include those traditionally studied within geology and geophysics. Processes with characteristic timescales of decades to centuries, which unite the fluid and biological Earth, are discussed in Chapter 4. The study of paleoclimate (Chapter 5) provides a crucial link between the two and underscores the importance of solar influences upon the Earth system.

Chapter 6 discusses the importance of modeling, necessary for organizing our knowledge of the Earth system and simulating future global trends. Chapter 7 surveys recent trends in instrumentation and technology, which offer outstanding opportunities for vigorous advances in knowledge in both the near and far terms. Of particular note are new capabilities for both spacecraft and *in situ* measurements, together with the increases in computing power needed for forthcoming generations of observational, data-analysis, and modeling efforts. Chapter 8 describes the characteristics and evolution of the observing and information systems needed for Earth system science. While the general characteristics of such systems have long been recognized, their practical implementation has often been neglected or accorded low priority, to the detriment of research progress.

The ESSC recommended program is presented in Chapter 9. The seven essential program components are supplemented by extensive and detailed tables setting forth the observations and related studies required for research progress over the next 20 years or so. The roles of U.S. federal agencies are considered within the context of an international effort directed toward an understanding of Earth evolution and global change. A summary of recommended U.S. space missions through the end of the century and their implementation schedule completes the primary material of the report.

1.F. SCOPE OF THIS REPORT

The present report reflects two fundamental restrictions in scope. One restriction is that imposed by the committee's definition of the Earth system, which is here considered to lie within the mesopause of the atmosphere, some 80-90 km above the Earth's surface. Although highly relevant aspects of ionospheric, magnetospheric, and solar-terrestrial studies are thereby excluded from this report, the important influence of the sun on the Earth system is considered in Chapter 5 (see particularly Section 5.B and box titled, "The Sun—The Critical Driver").

In addition, attention is restricted throughout this report to the physical, chemical, and biological processes that interact to determine the evolution of the Earth system and to produce global change. We have explicitly excluded discussion of economic, social, or political factors, since these issues lie outside the mandate and professional expertise of the Earth System Sciences Committee. Human influences on the Earth system are here considered simply as additional system inputs in the form of activity scenarios, such as conjectured time sequences for the burning of fossil fuels or patterns of land use. It is anticipated that a related but separate program will be developed to consider directly the economic, social, and political questions raised by our advancing knowledge of the Earth system, such as the impact of climate change on agricultural productivity or strategies for water-resource management.

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 five to ten volcanoes and the occurrence of two to five El Niños; and it is the period over which we 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) of the National Research Council, U.S. National Academy of Sciences (National Academy Press, Washington, D.C., 1985).

CHAPTER 1

RESEARCH FOR OUR GLOBAL FUTURE

Summary and Key Points

EARTH SYSTEM SCIENCE

◆ The two traditional motivations for Earth science are an understanding of the Earth as a planet and the search for practical benefits from such research.

◆ Earth system science treats the Earth as an integrated system of interacting components, whose study must transcend disciplinary boundaries.

◆ Earth system science has been stimulated by the maturation of the traditional disciplines, a global view of the Earth from space, and the increasing role of human activity in global change.

◆ On timescales of thousands to millions of years, Earth processes are driven both by internal energy and the external energy of solar radiation.

◆ On timescales of decades to centuries, Earth processes are dominated by the physical climate system and the biogeochemical cycles, with human activities playing an increasing role in both.

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

NOW IS THE TIME TO ACT

◆ The reality of global change on the timescale of a human lifetime furnishes a new and urgent motivation for Earth studies.

◆ These opportunities favor immediate action: maturation of scientific knowledge, new technology, and heightened worldwide political awareness and interest.

ROLE OF SPACE AND *IN SITU* OBSERVATIONS

◆ Space techniques can make an outstanding contribution to the study of Earth evolution and global change.

◆ Space observations need to be complemented by *in situ* studies of Earth properties.

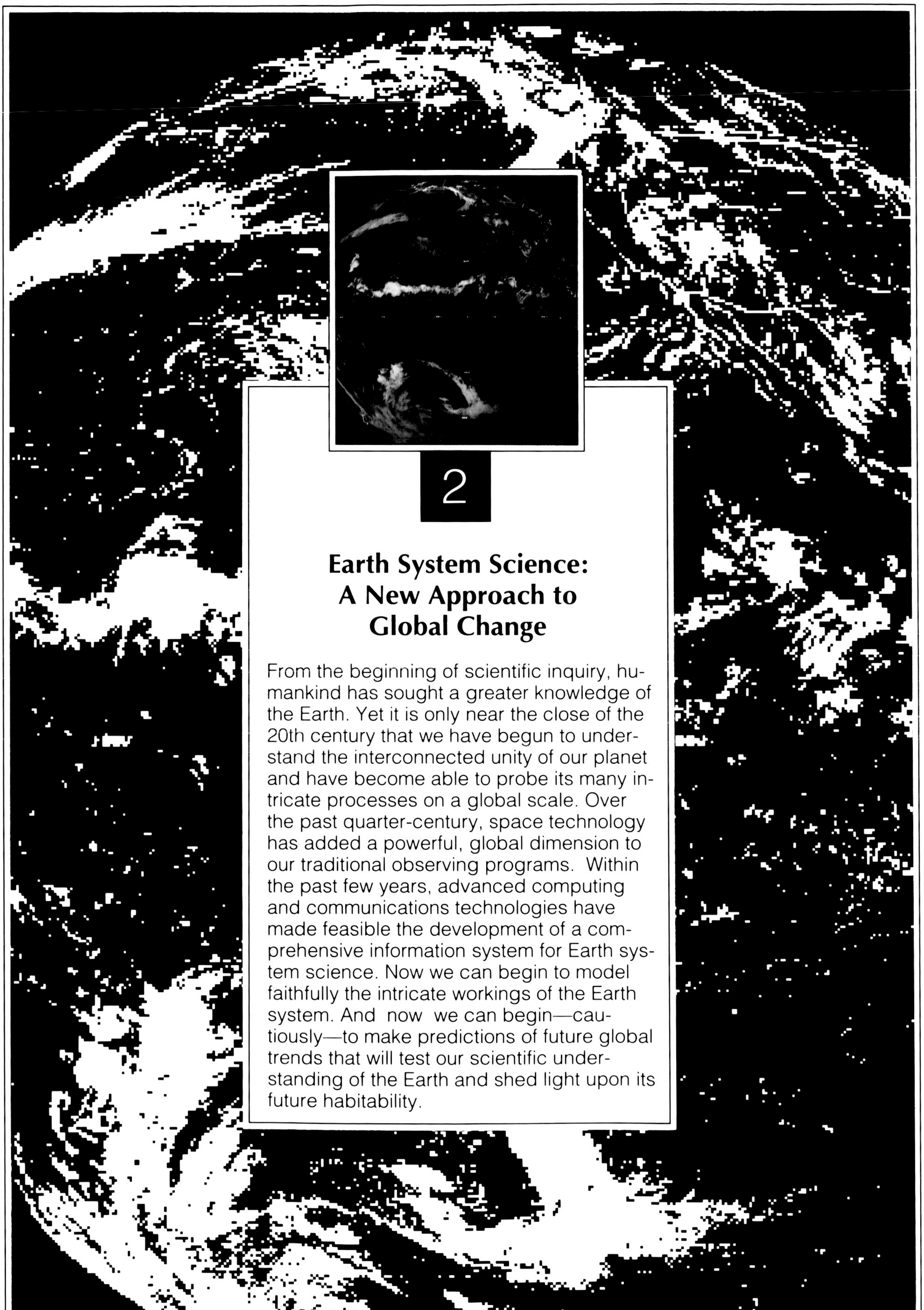
ESSC RECOMMENDATIONS

◆ The ESSC recommends in this report a coordinated research program to be carried out by NASA, NOAA, NSF, USGS, DoE, ONR, and other federal agencies.

◆ The anticipated achievements of the ESSC recommended program include global measurements, documentation of global change, predictions of future global trends, and an information base that will be key to informed decision-making.

◆ Federal agencies must act to ensure that the present momentum for the initiation of such a program not be allowed to dissipate.

◆ The present report is restricted to consideration of scientific issues; discussion of economic, social, or political factors has been explicitly excluded.



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Earth System Science: A New Approach to Global Change

From the beginning of scientific inquiry, humankind has sought a greater knowledge of the Earth. Yet it is only near the close of the 20th century that we have begun to understand the interconnected unity of our planet and have become able to probe its many intricate processes on a global scale. Over the past quarter-century, space technology has added a powerful, global dimension to our traditional observing programs. Within the past few years, advanced computing and communications technologies have made feasible the development of a comprehensive information system for Earth system science. Now we can begin to model faithfully the intricate workings of the Earth system. And now we can begin—cautiously—to make predictions of future global trends that will test our scientific understanding of the Earth and shed light upon its future habitability.

2.A. HISTORICAL PERSPECTIVE

The recognition of the Earth as a sphere occurred in antiquity and permitted the prediction of eclipses. In the third century B.C., Eratosthenes estimated the Earth's circumference by comparing noontime sun angles at locations 800 km apart. Following Copernicus' revival of the idea of heliocentricity in the 16th century, discovery, exploration, and scientific reasoning led to a reasonably accurate description of the Earth and its place in the cosmos. Man's curiosity and economic pressures spread people over the world; the navigators of many nations sailed the globe and took the measure of the Earth.

In the 17th century, Isaac Newton equated acceleration to specific force and thereby explained planetary dynamics, including the Earth's rotation and the lunar and solar origin of tides. In the 18th century, Benjamin Franklin studied atmospheric electricity and determined the path of the Gulf Stream; James Hutton established the concept of geological time and inferred the existence of the Earth's internal heat engine. In the early 19th century, Charles Lyell established a dynamic approach to geological Earth history, and Charles Darwin integrated the Lyellian approach with original observations of biological change to establish a theory of biological evolution (Figure 2.1). With this background, and with the explosion of new ideas in basic physics, chemistry, and mathematics, the stage was set for the development of a quantitative scientific study of the Earth in the 20th century (Figure 2.2).

The recognition of radioactivity in rocks enabled geologists to determine early in this century that the Earth is billions of years old. Geological and biological observations yielded the first clues to a dynamic Earth with drifting continents and changing magnetic poles. New ideas about the origin of the planets in the solar system were supported by accurate measurements of the elements in the Earth and, through spectroscopy, in the sun and other stars.

The 1940s and 1950s brought significant new developments. The extensive atmospheric observations of the 1940s, new theory, and the advent of digital computers led to the introduction of numerical weather prediction in 1948, demonstrating that knowledge of the present could indeed provide quantitative inferences about the future. The dawn of the Space Age in 1957 stimulated a new and widespread interest in global Earth studies.

The International Geophysical Year (IGY) in 1957-58 brought together many disciplines and nations and marked a major change in studies of the Earth, leading to exploration of distant oceans and polar regions, and producing new techniques for probing the Earth's interior. The Earth had been thought of as a relatively static body composed of three major parts: core, mantle, and crust. Variations in the orbits of the first IGY satellites revealed, however, a set of large-scale gravitational anomalies that we now believe to reflect convection in the Earth's mantle. Moreover, in the decade after IGY, new information from many sources led to a revolutionary new model of the Earth—plate tectonics—which recognized the planet as a dynamic, evolving body. In this model, the outer shell is composed of lithospheric plates moving in response to deeper convection currents that shape the continents and produce mountain ranges. This new view brought a global perspective to continental geology by stimulating a deeper understanding of rock structures and historical events, both on land and in the oceans.

Advances in oceanic and atmospheric sciences were fully as dramatic. New measurements from the ocean bottom and from ice cores supported the theory that ice ages are caused by periodic and predictable changes in the Earth's orbit. New oceanographic techniques began to give a global view of ocean waves, currents, and eddies, of ocean mixing, and of the distribution of heat, salt, and nutrients in the ocean interior. Improvements in atmospheric observations and computer models brought new capabilities to the simulation and prediction of global atmospheric motions. Weather satellites began to produce global data on cloud distributions and evolved to yield sophisticated measurements of winds and temperatures that produced significant improvements in weather forecasts.

An area of intense interest over the past two decades has been the global interactions of the ocean and atmosphere that produce major climate anomalies or planetary oscillations, such as El Niño and its atmospheric partner, the Southern Oscillation. Scientists have recognized the need for improved observations and more powerful computers to understand (and perhaps to predict) such complicated, global-scale phenomena. A substantial increase in atmospheric carbon dioxide was also documented during this period, and there was increasing recognition that this trend presented a major challenge to the atmospheric, oceanic, geological, and biological sciences. No one of them could deal alone with the complex problem of how the carbon cycle operates to produce the observed increase.

The past decade has also seen a revolution in our appreciation of the chemistry of the global environment and its susceptibility to change. This revolution has been generated by the recognition that the Earth's protective ozone layer is controlled by the complex interplay of atmospheric chemistry and circulation, and that increases in trace gases (e.g., the chlorofluoromethanes, or CFMs) could seriously deplete the ozone layer over the next several decades. More recent research has shown that concentrations of the important "greenhouse gases" methane and nitrous oxide are increasing at rates sufficient to ensure that they will play roles as important as that of carbon dioxide in warming the globe during the next century. We know that both of these gases are emitted in the course of microbial activity on land and in the oceans; however, we cannot yet identify the major sources or predict how these sources might change on a global scale. More generally, other aspects of atmospheric, oceanic, and land-surface chemistry have also revealed the need to understand global biogeochemical cycles of sulfur, nitrogen, and their oxides, as well as hydrocarbons, such as methane.

We have thus, in the 1980s, reached an exciting point in our attempt to know the Earth. Our research has led directly to the concept of an Earth system and a scientific approach that considers the Earth as a complex, evolving body, characterized by ceaseless change.

2.B. EARTH SYSTEM PROCESSES

Two primary conclusions have emerged from contemporary Earth-science research. First, change on a planetary scale is the result of interactions and feedbacks among the Earth's different subsystems—the atmosphere, ocean, mantle and crust, cryosphere, and biological systems. Moreover, change on any temporal scale involves interactions among Earth system processes that occur on diverse timescales.

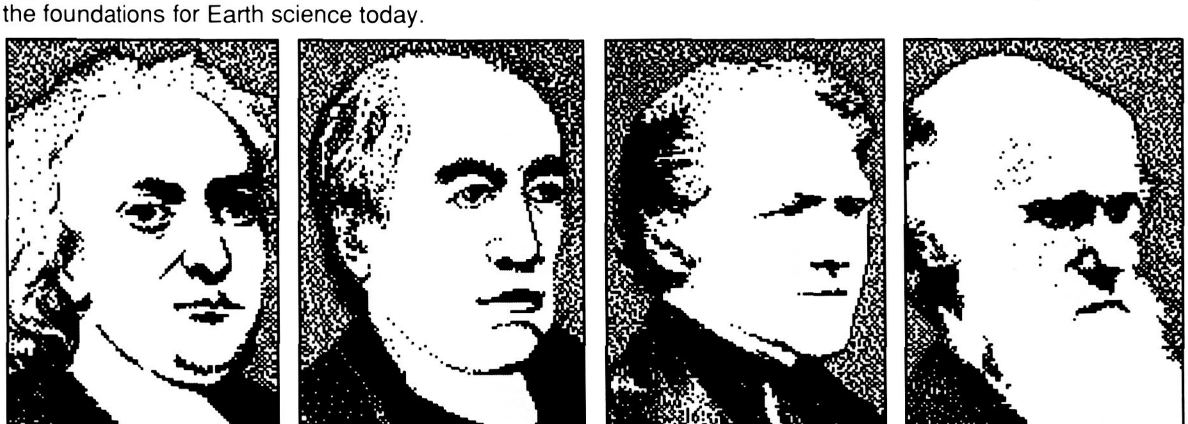
The traditional Earth sciences have, in general, each been concerned with structure and process within specific subsystems and within specific temporal ranges. In order to study and understand change on a planetary scale, we must therefore integrate the efforts of the Earth sciences and take a broader, global view. This is the task of Earth system science, which aims to understand the causes, processes, and perhaps the limits of variability of planetary change.

Consider Earth from the distant view made possible by space technology. The planet we see—clouds swirling over the blue ocean—has been properly referred to as the "Blue Planet." How might we describe the processes and the evolution of this object? Ideally, we seek to represent its state at any time by a collection of variables and to determine how each of these variables will change with time—that is, we seek to treat the Earth as a dynamical system. Clearly a dynamical system that would represent all processes and change on the Earth would be an immensely complicated mathematical structure, which is at present beyond our powers to develop. In practice, then, we will often choose to modify that dynamical model—for example, use only part of it—in order to examine processes on certain timescales or in order to solve specific problems.

To gain some perspective on the dynamics of the Earth system, we can proceed to identify the characteristic spatial and temporal scales of relevant processes—such as a weather system or plate tectonics—and to indicate their positions on a diagram with spatial and temporal scales as axes (Figure 2.3). Such a diagram includes many of the interesting phenomena that have already been studied by the Earth sciences, ranging from turbulence to mantle convection, and from the annual cycle of vegetation to the origin of the Earth and of life.

However, not a single process or phenomenon shown in Figure 2.3 is adequately

Figure 2.1 NEWTON, HUTTON, LYELL, AND DARWIN. These scientists were among the many who laid the foundations for Earth science today.



understood; for not one of them do we adequately comprehend the interactions with the others. Despite the fact that we isolate these processes on this diagram, they are influenced by other processes—sometimes in other subsystems, sometimes in other ranges of temporal and spatial scales. The efforts of the traditional Earth sciences to understand these processes, both to advance our knowledge of the planet and to secure practical benefits from this knowledge, must therefore be continued and strengthened.

Earth system science takes as its major task the description and understanding of the planetary-scale change represented by a broad horizontal band spanning the top of Figure 2.3, reflecting a range of spatial scales approximating the radius of the Earth. Earth system science, founded on the Earth sciences, integrates all of them by taking a broader, global view of planetary-scale evolution and change. It is one of the first realizations of Earth system science that such planetary-scale change occurs in a wide band of timescales and is driven or modified by processes in all temporal ranges.

Five distinct temporal bands can be used to define the major timescales involved in global change. These bands are:

• **Millions to Billions of Years.** The Earth formed rapidly—within a hundred million years—and since that time a metallic core (responsible for the magnetic field) has remained largely isolated from the overlying convective mantle and moving lithosphere. The characteristic timescales for the operations of these systems are millions of years; the evolution of life and the associated development of the present chemical composition of the atmosphere occurred on similar timescales.

• **Thousands of Years.** The oscillations between ice ages and interglacial periods (with associated variations in atmospheric chemical composition), the development of soils, and the distribution of biological species occurred largely in response to changes in the Earth's orbit around the sun that recur in cycles of tens of thousands of years.

• **Decades to Centuries.** The changes that threaten the viability of some forms of life on the planet—changes in climate, chemical composition of the atmosphere, patterns of surface aridity or acidity, and in terrestrial and marine biological systems—must be understood and anticipated during the next decade to century.

• **Days to Seasons.** Weather phenomena, eddies in ocean currents, seasonal growth and melting of the polar sea-ice covers, surface runoff and weathering, and the annual cycle of plant growth are all confined to timescales regulated by the annual cycle of insolation. A large part of the feedback from the biogeochemical cycles occurs through the alteration of the radiative processes that supply energy to the major subsystems. Earthquakes and volcanic eruptions are episodic manifestations of adjustments taking place within the solid Earth over much longer timescales; the sudden violence of such cataclysmic events obscures the fact that tens to hundreds of years are required for accumulation of the energy needed for a repetition of the event.

• **Seconds to Hours.** The fluxes of mass, momentum, and energy among the land, the ocean, the ice, the atmosphere, and the biota are all dominated by processes with time-

Figure 2.2 EARTH SCIENCE in the 20th century.

Research Milestones	
1905	Ionosphere revealed by trans-Atlantic radio transmission
1906	Radioactive dating of the age of the Earth
1915	Continental-drift hypothesis: evidence, but no mechanism
1920	Milankovitch theory of ice ages
1930	First comprehensive theory of ozone layer
1948	Beginning of numerical weather prediction
1957	Beginning of International Geophysical Year (IGY) and the Space Age
1958	Discovery of Van Allen radiation belts by Explorer-1
1958	Initiation of long-term measurements of atmospheric carbon dioxide
1959	Publication of accurate map of North Atlantic sea floor
1960	First satellite images of Earth
1960s	Recognition of lithospheric plate structure and mechanism for continental drift
1971	Age of Earth-moon system confirmed at 4.5 billion years by moon-rock dating
1972	Launch of LANDSAT-1 for land-surface observations
1970s	Recognition of destruction of stratospheric ozone by catalytic cycles
1977	Discovery of anaerobic life within ocean spreading centers
1978	Launch of Seasat and Nimbus-7 for oceanic and atmospheric observations
1981	Study of the Earth's aurora from space
1983	Direct measurement of continental drift by VLBI
1980s	Intensive study of Antarctic "ozone hole"
1986	International Geosphere-Biosphere Programme (IGBP) endorsed by International Council of Scientific Unions
1995	Initiation of observing program for Earth system science

scales shorter than 1 day. Over the land and the ocean, these exchanges occur through the medium of turbulent transports that are themselves responsive in part to diurnal heating cycles.

The first two of these temporal bands, referring to longer timescales, contain the phenomena that have traditionally been the domain of the geosciences—geophysics, geology, and geochemistry. The last two bands have been emphasized in the efforts of the atmospheric, biological, and oceanic sciences. The middle band contains those processes and effects that appear directly in global change on timescales of decades to centuries.

Biological processes take place on all timescales, but those occurring in the middle band are of paramount importance to the concerns and planning of human societies. To meet this challenge, Earth system science must combine the knowledge of the geosciences, the atmospheric and oceanic sciences, and a developing knowledge of the Earth's biological systems to understand, and perhaps predict, the evolution of the Earth system on the timescale of a human lifetime. This approach must therefore unravel the interactions between phenomena and processes that combine to produce planetary-scale changes on the intermediate timescales, and then integrate this new knowledge into a coherent scientific structure that reflects the operation of the Earth as a dynamical system. Finally, the validity of this structure must be tested against the evidence of long-timescale processes contained in the geological record.

By examining our present knowledge of the processes and phenomena exemplified in Figure 2.3, we can identify what are probably the most significant interactions among them, quantify that understanding in terms of explicit models, and devise observations and experiments that test many of the important conclusions. In this way, we construct a view of the Earth system—not in terms of real objects or technology, but rather in terms of inputs and outputs, subsystems, and feedback loops. The ingredients sampled in Figure 2.3 are legion, but a structure may be developed by grouping as subsystems the more closely interacting processes and phenomena, and by identifying the minimum information necessary to describe the linkages among these groups.

At the highest level, this structure is determined primarily by the question being asked—in this case: What are global changes that will occur in response to certain conjectured inputs, and what is the level of inherent variability from which those changes should be measured? At lower levels, the structure may well coincide with patterns that have previously been identified within individual disciplines; at still lower levels, it may resemble individual research projects. A coherent view of the entire system can be made to emerge by summarizing each level in terms of quantitative models—always asking the question: How much difference does it make?—and then re-examining the basis for those models.

Of course, advances in science are usually more complex than this simple paradigm would suggest. Nevertheless, as we begin to understand how the Earth functions in a global, systemic way, as we begin to assemble its wonder in the framework of an appropriate dynamical system, we shall also begin to understand more clearly the history of this planet and perhaps become able to foretell some key aspects of its future.

2.C. HOW THE EARTH SYSTEM FUNCTIONS: CONCEPTUAL MODELS

The essential questions of Earth system science—How does the planet work? How did our planet evolve? What is its future?—will only be answered when the observations of the Earth system are assembled into a conceptual framework that permits quantitative simulations or predictions to be developed. A key component of our research strategy is the use of global and process observations to create models both of the subsystems and of the Earth system itself, and the use of those models to refine the observing system.

Such models will take a number of forms. Some will be descriptive, specifying, for example, the average flows of energy and material among soil, forest, and atmosphere, or the gross relative motion of the major tectonic plates. Some may be mathematical, such as the equations of motion that describe the evolution of atmospheric or oceanic processes, or the generation of the geomagnetic field by fluid motion in the Earth's core. Others may be numerical or computer models, such as those now used to predict the weather 5-10 days in advance or to reveal how regional strain builds up in the vicinity of active geological faults.

2.C.1. Timescales of Thousands to Millions of Years

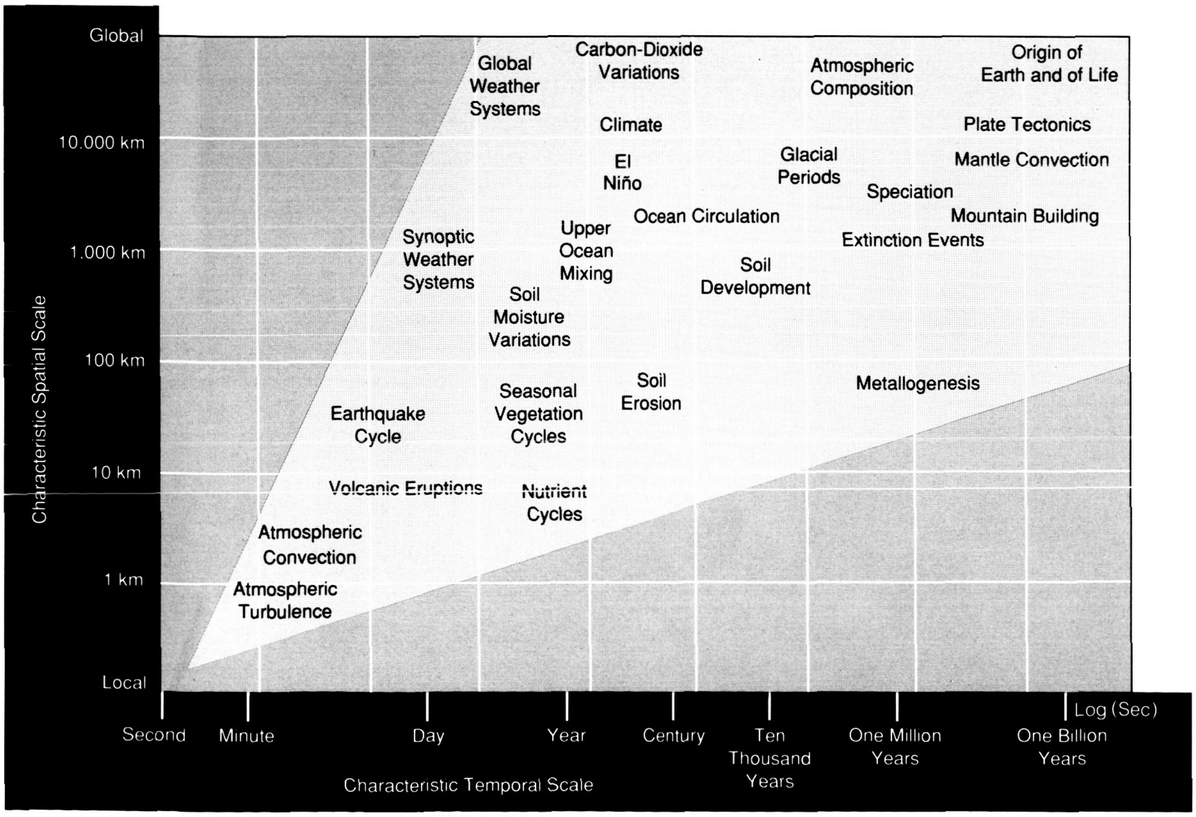
Models of Earth system processes on longer timescales have, until recently, been largely descriptive, but quantitative observations are now permitting the development and testing of numerical models. An overall framework, integrating many of the major components that must be studied in order to understand and describe the Earth system on longer timescales, is presented in Figure 2.4.1 (foldout). The figure also shows couplings among these components.

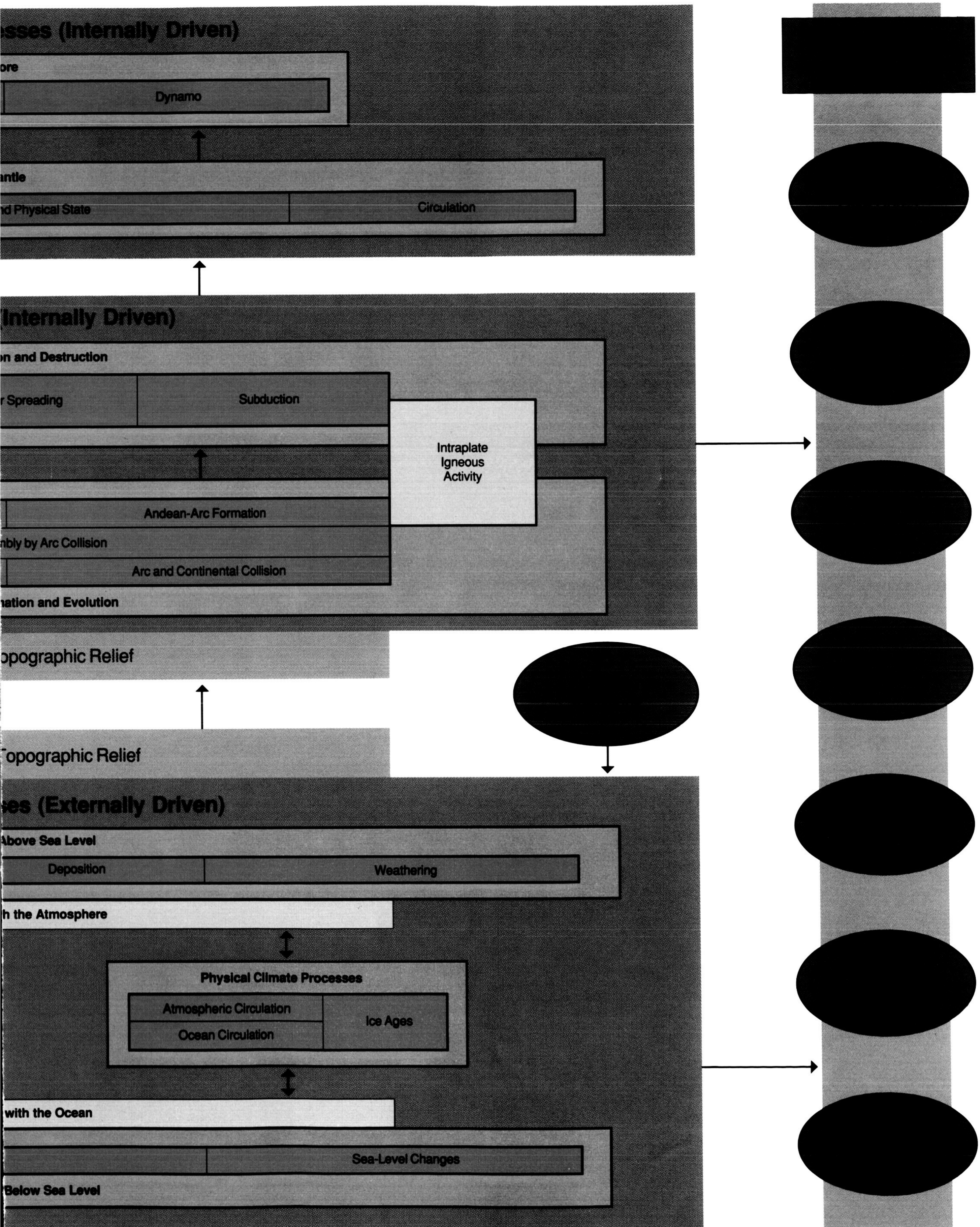
By and large, processes operating over long timescales take place either at considerable depth within the solid Earth or within a thin veneer at its surface. Since these regions are not generally accessible to direct observation, much of what is known about them is inferred from indirect measurements, through analogy with processes that can be observed at the surface today and laboratory simulations under elevated pressure and temperature, within the framework of broad, conceptual models. However, the long timescales themselves imply that concepts in this field generally cannot be based on current observations and experiences. Rather, they are developed through an interpretation of events in the remote past. Predictions on these timescales are not generally feasible, notable exceptions being predictions of earthquakes and volcanic eruptions (phenomena which have short-term effects but which result from long-term processes).

The core and mantle processes and the plate-tectonic processes shown as major groupings in Figure 2.4.1 are both driven by energy internal to the Earth system (radioactivity and primordial heat). These processes are connected to those driven by solar energy, which, in the case of solid Earth, involve erosion and the transport and deposition of sediments. Interactions between the internally and externally driven processes are manifested primarily through the generation and degradation of topography (for detailed discussion of all of these processes, see Chapter 3).

As Figure 2.4.1 indicates, life itself has had a significant effect on the solid Earth: it affects the oxygen balance of the atmosphere and, in turn, the chemistry of surface deposits. It also affects the speed of weathering and the chemistry of the oceans and ocean deposits. On the other hand, long-timescale processes can also affect the biosphere. It seems quite possible that there were occasions, suggested in the geologic record, when normal evolution was rapidly influenced by cataclysmic events—for example, by huge meteorite impacts—that may have caused major extinctions of vulnerable species. It is also quite possible that such extinctions were caused by volcanic eruptions (or eras of volcanic activity). Studies of such events in the geologic record can thus provide essential data on the boundary conditions for current-day climate models.

Figure 2.3 EARTH SYSTEM PROCESSES: Characteristic spatial and temporal scales.





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Atmospheric Circulation
Ocean Circulation
Ice Ages
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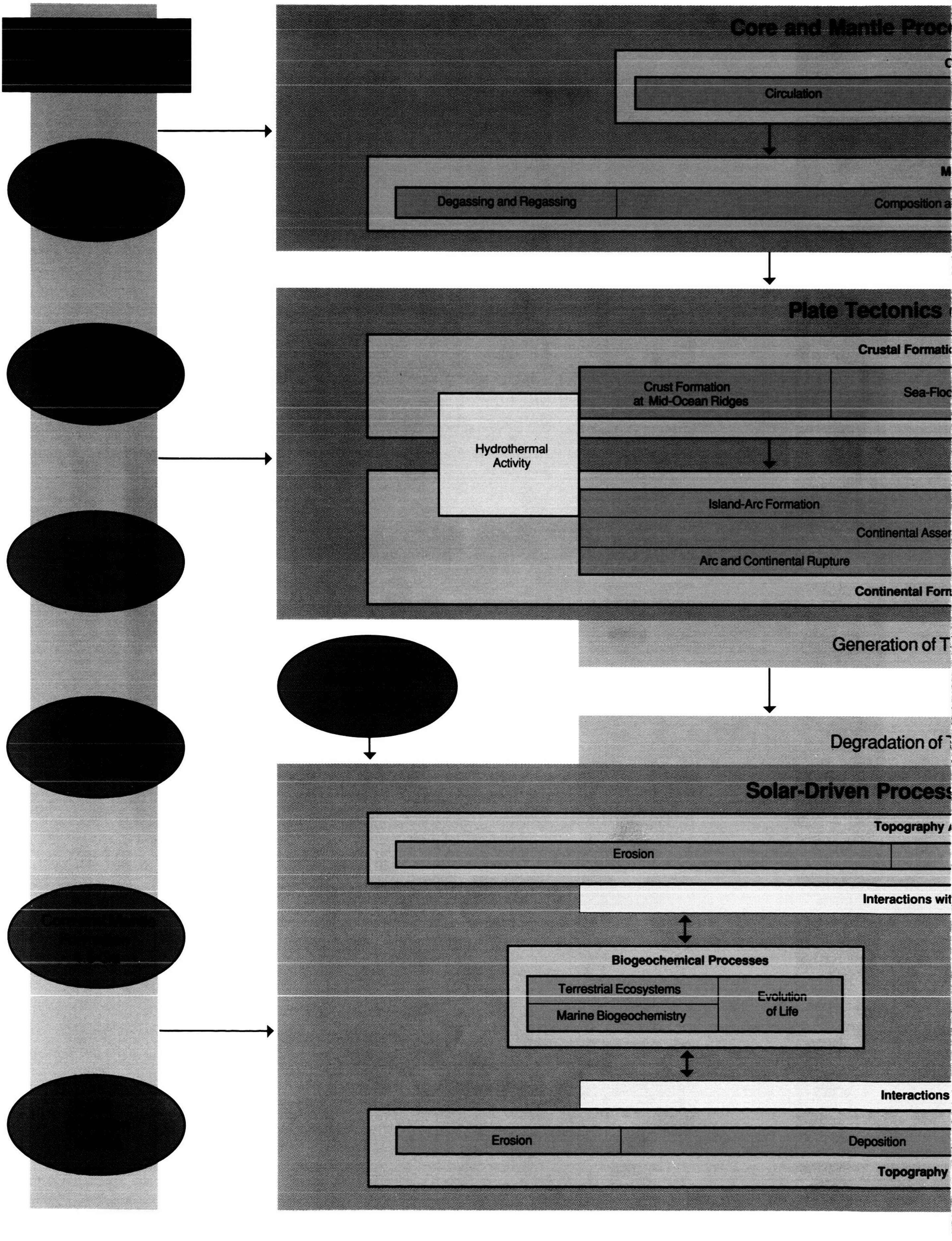
Sea-Level Changes
Below Sea Level

Figure 2.4.1 CONCEPTUAL MODEL of Earth system processes operating on timescales of thousands to millions of years.



Global Change: Thousands to Millions of Years

On timescales of thousands to millions of years, the inexorable processes of solid-Earth change dominate all others. A variety of early-Earth processes, ranging from initial accretion from planetesimals to the origin of life, occurred billions of years (Ga) before the present and set the stage for the long-term evolution of the Earth system. Following these early events, the history of the Earth has been determined by processes operating within three broad classes:

- Core and mantle processes, which govern the Earth's primary magnetic field and involve nearly all its mass and kinetic energy;
- Plate-tectonic processes, acting in general to generate surface topography through crustal formation and destruction and through continental formation; and
- Solar-driven processes, acting in general to degrade topographic relief both above and below sea level, but including as well the richness and diversity of the physical climate system and the biogeochemical cycles.

The long-term evolution of the Earth has also been influenced by bombardment by meteorites and comets, and by periodic variations in insolation arising from changing Earth-orbital parameters.

This conceptual model is, for the most part, at an early stage of development; however, the primary interactions among subsystems, indicated by arrows, are already beginning to be probed. Taken as a whole, the model produces, as output, a record of Earth history. While central attention has traditionally been paid to the dating of major Earth events through the geological and fossil records, a study of these long-timescale processes can also yield details of past climatic variations on the Earth, which are of crucial importance for the concurrent study of processes operating on shorter timescales and thus relevant to human habitability. An extensive discussion of global change on timescales of thousands to millions of years is given in Chapter 3.

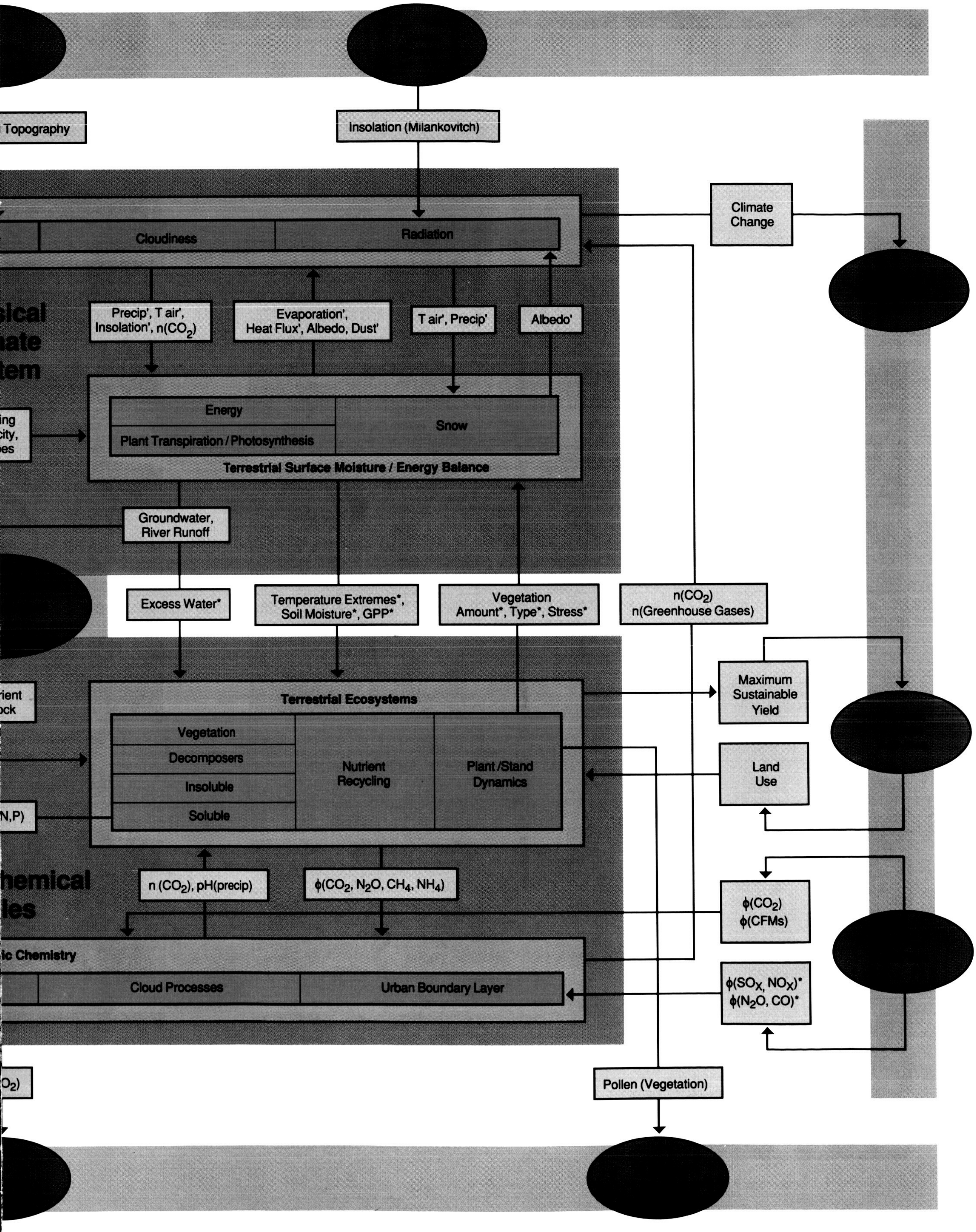
Global Change: Decades to Centuries

It is on timescales of decades to centuries that natural change has major effects on humanity, and that the effects of human activity on global processes are most pronounced. In this temporal range, two great sets of processes are at work:

- **The physical climate system, which incorporates the subsystems labeled atmospheric physics/dynamics, ocean dynamics, and terrestrial surface moisture/energy balance; and**
- **The biogeochemical cycles, which incorporate the subsystems labeled marine biogeochemistry, terrestrial ecosystems, and tropospheric chemistry.**

The stratosphere/mesosphere subsystem straddles the conceptual division between these two sets of processes. The physical climate system and the biogeochemical cycles are, furthermore, intimately connected by the ubiquitous presence of water in the forms of liquid water, water vapor, and ice.

The processes or information sources contained within the ovals represent inputs from, or outputs to, the external environment or processes that operate over significantly longer timescales. Each of the arrows that connect subsystems, inputs, and outputs is labeled with the information required to establish a quantitative relationship; the arrows thus chart the flows of information among presently evolving computer simulations of Earth system processes on these timescales. An extensive discussion of global change on timescales of decades to centuries is presented in Chapter 4; paleoclimate, which links these processes with those operating over longer timescales, is discussed in Chapter 5.



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Snow
Terrestrial Surface Moisture / Energy Balance
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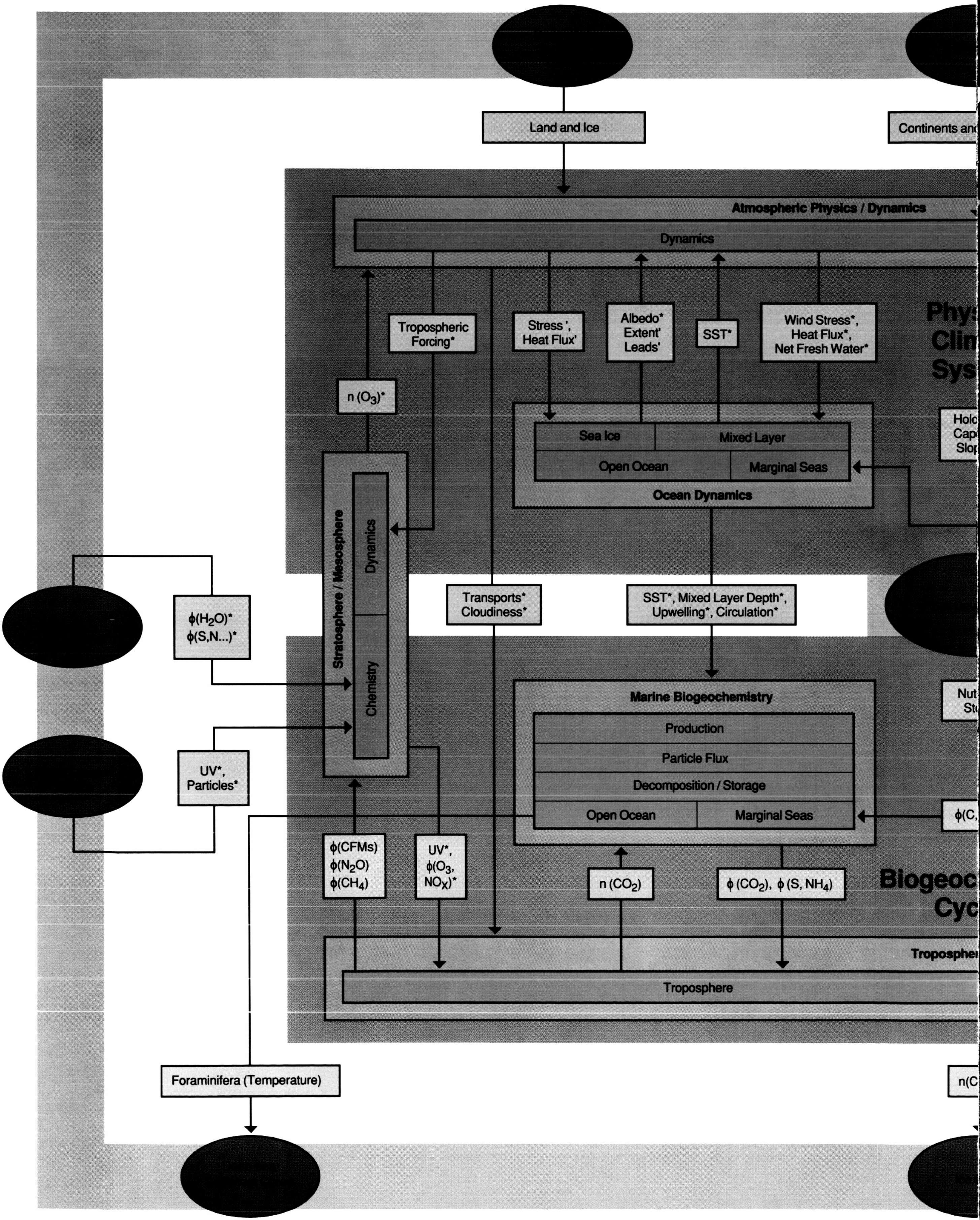
n (CO$_2$), pH(precip)
ϕ(CO$_2$, N$_2$O, CH$_4$, NH$_4$)
ϕ(CO$_2$) ϕ(CFMs)
ic Chemistry
Cloud Processes
Urban Boundary Layer
ϕ(SO$_X$, NO$_X$)* ϕ(N$_2$O, CO)*
O$_2$)
Pollen (Vegetation)

Figure 2.4.2 CONCEPTUAL MODEL of Earth system process operating on timescales of decades to centuries.



' = on timescales of hours to days • = on timescales of months to seasons ϕ = flux n = concentration

2.C.2. Timescales of Decades to Centuries

An approximate summary of our present concepts of how the Earth system functions on timescales of decades to centuries is presented in Figure 2.4.2 (foldout). This should be viewed as a conceptual architecture for a computer model, potentially suitable for predictions of change, but also useful as an organizing concept for presentation of the system structure. The figure is dominated by two large rectangles representing the physical climate system and the biogeochemical cycles, which interact in a variety of ways (see Chapter 4). The major subsystems (e.g., ocean dynamics, marine biogeochemistry), shown as boxes in Figure 2.4.2, 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 attached arrows denote inputs from, or outputs to, an external environment.

Changes in inputs to this conceptual model of the Earth system—such as cycles of solar activity, burning of fossil fuels, and patterns of land use—are all treated as scenarios, specified by the investigator in order to examine their effects on the model state variables. The outputs are manifold, corresponding to every observable phenomenon about which some information may be available. Those of particular concern to model testing through examination of past climates have been singled out for explicit mention. It should be noted that human activities are treated as outside the major feedback loop. Although this has major advantages, it does imply that a substantial additional activity, not addressed in this report, is necessary to evaluate the significance of changes in climate and ecosystem balances for specific aspects of societal concern, such as water resources, agricultural productivity, and sea level near coastal communities. Such evaluations tend to involve economic, social, and political as well as purely scientific factors and are not considered in this report.

2.D. RESEARCH APPROACH OF EARTH SYSTEM SCIENCE

The research approach of Earth system science consists of four steps:

- The acquisition of observations;
- Analysis and interpretation of the observational data;
- Construction of (and experimentation with) conceptual and numerical models; and
- Verification of the models, together with their use to furnish statistical predictions of future trends.

These steps, moreover, form a cyclic rather than a sequential procedure, as the verification of models requires their testing and revision through comparisons with the observations (Figure 2.5). The models, in turn, often provide new insight into the observations required for research progress.

The research approach outlined above is, in itself, not new. A great many other scientific investigations proceed essentially in this way, and the approach has already been applied to the study of individual Earth components. What is new is the application of this approach to the Earth system as a whole. Such a venture increases enormously the range and quantity of observations to be accommodated, the scope of data analysis and interpretation, and the complexity of the models themselves.

This program cannot be effectively pursued without the simultaneous development of a highly capable information system for Earth system science as an integral part of the research endeavor. The information system will be required to receive, process, and archive a new generation of observational data; to promote data analysis and interpretation through new computational techniques and the sharing of results among different research groups; to support the development of advanced numerical models that treat explicitly the interactions among the Earth's components; and to permit the extrapolation of present results to identify and simulate future trends in global variables. An information system equal to these tasks is thus a necessity for the research program presented in this report.

Inherent in the approach of Earth system science is the desire for a quantitative understanding of the Earth system and the many interactions among its components, rather than merely qualitative descriptions. We therefore seek to specify the state of the Earth system, as a function both of space and of time, through a suitable set of state variables, and to apply the physical, chemical, and biological laws that relate the present state to past and future states. In some cases, such as ocean dynamics, appropriate state variables are almost self-evident from our understanding of Newtonian mechanics; only the compromises necessary to restrict the description to a manageable number of degrees of freedom cause controversy and uncertainty. In other cases, such as terrestrial ecosystems, we lack an adequate understanding of the basic chemical and biological laws governing assemblages of complex organisms and do not yet know what set of state variables would be adequate to describe the major dependencies within the ecosystem.

Global Earth observations are basic to achieving such an understanding—particularly sustained, long-term measurements of those global variables required to specify the present state of the Earth system. It is only through such measurements that we can record changes in the Earth system in a quantitative fashion, thus constructing the data base required to test theories of Earth evolution and global change. In addition, we must gather the observations needed for a fundamental description of the Earth and its history, as well as those more specialized observations required for process studies.

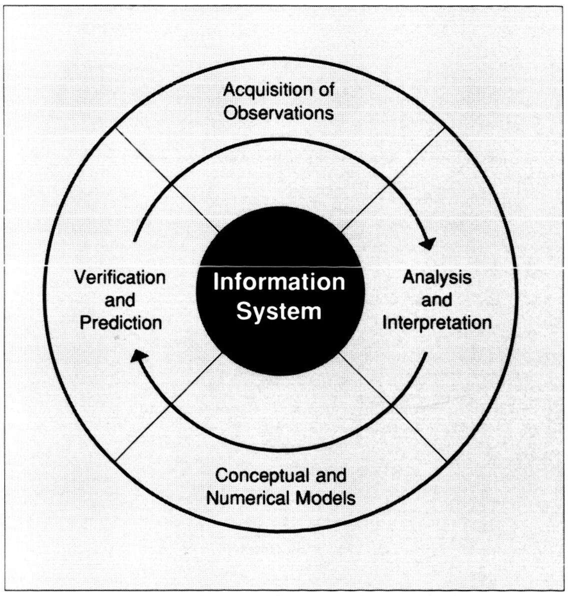
Through data analysis and interpretation, based upon existing knowledge and theoretical frameworks, we then seek to discern patterns in the data that can be explained in terms of processes—associations of phenomena governed by physical, chemical, or biological laws. The transition from pattern to process is a vital step in the transformation of qualitative knowledge into quantitative understanding. It is this step that reveals the appropriate group of state variables and the dominant dependencies among them.

Mathematical and numerical models of Earth system processes carry the analysis further, incorporating numerical algorithms for processes that permit quantitative links with other processes and hence the incorporation of interactions among them (see Chapter 6). Models that provide complete and explicit specification of the rates of change of system variables as functions of present values of the variables, external forcing effects, and other parameters are often referred to as dynamical systems. A differential equation (or equations) specifies the time-evolution of the system; future system states are obtained through solutions of an initial-value or boundary-value problem. Although this definition implies that the system evolution is deterministic, we know from experience with nonlinear subsystems of the Earth system that the solutions are strongly dependent upon initial conditions. Since initial conditions are rarely known precisely, the determinism may be illusory. The most we can expect from this procedure, therefore, is a correct representation of the statistical characteristics of the solutions, including information about major cyclic variations and the expected ranges of system variables. How far the system evolution would be predictable in detail, even with a perfect model, is a basic question that can only be addressed by a combination of numerical experiments with specific models and comparison with observations.

Modeling brings a number of other benefits to Earth system science. It provides a framework for assembling data and knowledge, and for stimulating theoretical developments. It provides both a motivation and a mechanism for promoting interactions among specialists in different disciplines. In addition, it supplies the only responsible means for conducting numerical simulations designed to show how the Earth system would respond to different input scenarios, such as variations in external forcing, disturbances by natural events (e.g., volcanic eruptions), or human activities.

Verification and prediction complete the cyclic research approach. The results of modeling efforts must, at the least, reproduce the present state of the Earth and explain its past. Comparisons with Earth-science data are stern tests for model features, frequently exposing their inadequacies while at the same time suggesting both new models and new observations. Well-founded models will also permit projections of global trends into the future. Models thus furnish a primary avenue for investigating the role of human societies in global change and the impact of a changing environment upon our descendants. While most such efforts are at present rather rudimentary, they hold the promise of identifying the key issues that human societies must come to terms with in the decades ahead.

Figure 2.5 RESEARCH APPROACH of Earth system science. The four steps are cyclically related and make use of a global information system.



Important Concepts and Terms

Certain important concepts and terms occur repeatedly throughout this report. A more extensive listing of these, together with additional detail, is given in Appendix E; here we provide a summary relevant to global observations, measurement systems, specific research topics, and information systems.

- Global variables—functions of space and time that describe the large-scale state and evolution of the Earth system.

- Global measurement—all of the activities required for the specification of a global variable, ranging from data acquisition to the generation of a data-analysis product, including estimates of the uncertainties in that product. A global measurement will often consist of a combination of observations from a spacecraft instrument (required for global coverage) and measurements *in situ* (needed to provide reference points for long-term accuracy).

- Sensor calibration—the relationship between input and output for a given measurement device.

- Measurement validation—the establishment of confidence in the numerical relationship between the calibrated sensor output (including any ancillary data required) and the actual variable being measured.

- Measurement system integrity—the tracking and documentation over the long term of all the causes of error or uncertainty in the final data-analysis product. These include: instrument calibration, adequacy of measurement validation, data coverage and sampling density, availability and quality of ancillary data, procedures for data analysis and reduction, the results of checks against independent measurements, and quantitative error analysis.

- Process—an association of phenomena governed by physical, chemical, or biological laws. Examples: the vertical mixing of ocean waters in the so-called surface mixed layer, the volcanic deposition of dust and gases into the atmosphere, eddy formation in the atmosphere and oceans, and soil development.

- Process study—an organized, systematic investigation of a particular process, designed to identify all of the state variables involved and to establish the relationships among them. Process studies yield numerical algorithms that connect the state variables and determine their rates of change; such algorithms are essential ingredients of Earth system models.

- Research foci—topics which, because of their importance and their data or facility needs, require a coordinated research approach over the next decade. Research foci are needed for a variety of reasons: to synthesize diverse bodies of knowledge into a coherent whole, to study a key process to produce improvements in understanding and algorithms for global models, or to gain the fundamental knowledge required for design of a measurement system for an essential global variable. (In a few areas, such as ecosystem dynamics, the issues are even more basic, e.g., the identification of the state variables that determine the large-scale behavior of the system.)

- Information system—all of the means for data receipt, transmission, processing, analysis, distribution, archiving, and access by external users, together with a unifying management and control structure. Provision must be made for storage and dissemination of a variety of data products—including primary data sets and both intermediate and final analyses—and for an interface providing connections to external computers, external data banks, and system users.

CHAPTER 2

EARTH SYSTEM SCIENCE: A NEW APPROACH TO GLOBAL CHANGE

Summary and Key Points

GLOBAL CHANGE

◆ Global change is the result of interactions and feedbacks among the Earth's components: core and mantle, lithosphere, hydrosphere, atmosphere, and biosphere.

◆ A scientific understanding of these interactions and feedbacks requires the Earth to be studied as a unified, dynamical system.

◆ Improvements in the prediction of future global trends over the next decade to century depend upon a better understanding of Earth system interactions.

EARTH SYSTEM PROCESSES

◆ Processes operating on longer timescales have traditionally been studied within the geosciences.

◆ Processes operating on shorter timescales—traditionally covered within the atmospheric, ocean, and biological sciences—are particularly relevant to the concerns and planning of human societies.

◆ In order to achieve an understanding of a process operating on one timescale, the effects of interactions with processes operating on other timescales must be considered.

MODELS

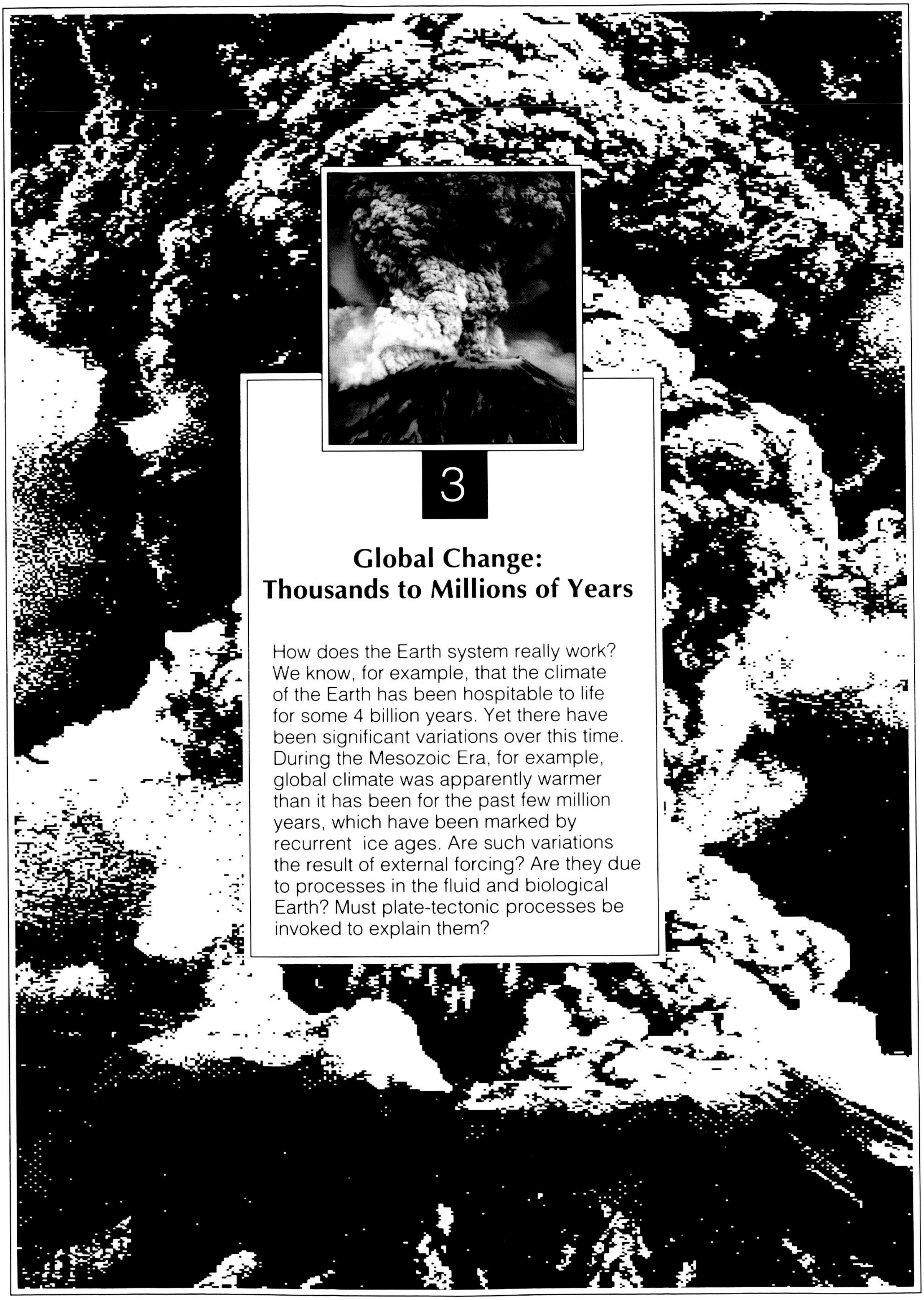
◆ Conceptual and numerical models of Earth system processes are a key component of the strategy for understanding Earth evolution and global change.

◆ Models are currently being developed to describe global change on two classes of timescales: thousands to millions of years, and decades to centuries.

RESEARCH APPROACH

◆ The research approach of Earth system science involves four cyclic steps: observations, analysis and interpretation, models, and verification and prediction.

◆ An information system for Earth system science is essential to implement this research approach and develop a unified understanding of the Earth system.



3

Global Change: Thousands to Millions of Years

How does the Earth system really work? We know, for example, that the climate of the Earth has been hospitable to life for some 4 billion years. Yet there have been significant variations over this time. During the Mesozoic Era, for example, global climate was apparently warmer than it has been for the past few million years, which have been marked by recurrent ice ages. Are such variations the result of external forcing? Are they due to processes in the fluid and biological Earth? Must plate-tectonic processes be invoked to explain them?

We do not know the answers to these questions. We do know, however, that an interpretation of processes operating in the past—which are responsible for how the Earth has evolved—frequently requires an understanding of similar processes operating in the present. Conversely, any attempt to predict future changes in the Earth system is perilous without attention to the past; the Earth's history reveals interactions that could otherwise be overlooked in present analyses, and it furnishes a record of the ranges of variability of global quantities that are crucial for the testing of current hypotheses and models.

Global change over long time intervals is inscribed in the rocks of the Earth. In general, this record is best for events in the recent past and becomes progressively less detailed for older eras extending back to 3.8 Ga (billions of years) before the present. Rocks reveal an immensely long (although incomplete) time series, providing unique information on the frequency of global changes and especially on the extremes to which these changes have extended. A clear message of this record is that, although catastrophic episodes have left their mark (e.g., the vast eruptions of the Yellowstone and Long Valley calderas and the extensive biological extinctions of 65 million years ago), the Earth's environment has never, since the initial evolution of life, been sharply inhospitable for very long. A striking illustration of this overall stability is that liquid water has been continuously present on the Earth for about the last 4 billion years.

3.A. SCIENTIFIC ISSUES

On timescales of thousands to millions of years, the Earth is driven by both internal (radioactive and primordial) and external (solar) energy (see again Figure 1.3). Two systems that are driven by internal energy can be usefully distinguished: a core-mantle system operating deep within the Earth, and a plate-tectonic system operating close to the Earth's surface, as shown in Figure 3.1, a simplified version of Figure 2.4.1. These systems interact largely through the production of plate material from the mantle and its subduction back into the mantle at convergent plate boundaries. This process, and others like it, are believed to have acted continually since early in the Earth's history. However, in the very earliest times—about the first 300 million years—other processes were responsible for establishing the gross planetary structure that influenced all subsequent developments. It was during this period that the familiar major components of the Earth system came into being: core, mantle, crust, oceans, atmosphere, and ultimately life.

The internally driven system produces, among other things, the Earth's topographic relief, such as ocean ridges and basins, mountain belts, and plateaus. It is through the alteration of topography that the interactions of the internally and externally driven systems are revealed. There is a major distinction between processes operating above sea level (e.g., weathering and erosion), in which rocks interact mainly with the atmosphere and surface waters, and those below sea level (e.g. sedimentation and diagenesis), in which the interaction is mainly with the ocean.

The register of the complex history of the Earth—the geological record—is fairly complete within the oceans but is there limited to the past 200 million years, the age of the oldest surviving ocean floor. Though less detailed, the record on the continents extends back to 3.8 Ga. The Quaternary record of the past 2 million years illustrates how rocks from the ocean floor and the continents preserve complementary information on the Earth system. Drill cores from the ocean floor have been used to show how variations in the Earth's orbital parameters have influenced climatic change during the latter part of the current glacial epoch, while the distribution of rocks on the continents has permitted determination of the former extent of ice caps, deserts, and vegetated areas at glacial maxima and minima. The investigation of these and other geological records is the key to understanding the history of the Earth and the operation of Earth system processes that function on longer timescales.

The fossil record, for example, has revealed that biological evolution has not been a continuous, smooth process but has instead been punctuated by several more or less cataclysmic events resulting in the sudden demise of many species. Debate continues as to the causes of these events; impacts of large extraterrestrial objects and widespread volcanic eruptions have both been suggested. Whatever the causes, species susceptible to these unusual events disappeared, and, following such events, new species burst forth into a relatively unconstrained environment. Both circumstances may have significantly altered the evolutionary process in ways that Darwin and his followers could not have known. It is important to study and understand the causes and results of these events so that we can understand both the history and the constraints of life on Earth.

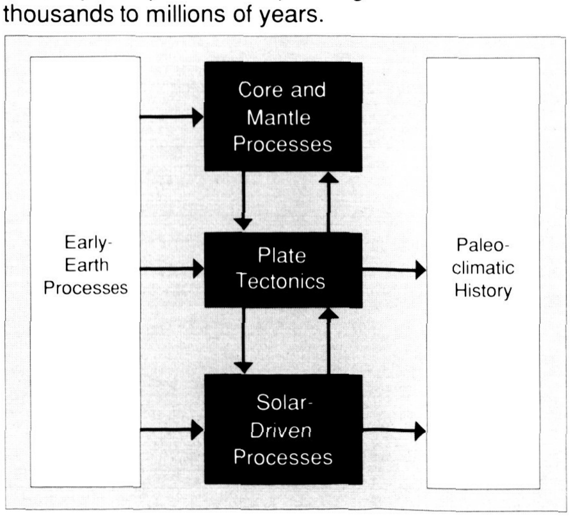
In the following sections, the key elements of such investigations will be discussed in terms of the categories illustrated in Figure 3.1: early-Earth processes (3.A.1), core and mantle processes (3.A.2), plate tectonics (3.A.3), and solar-driven processes (3.A.4). Paleoclimatic history is treated in Chapter 5.

3.A.1. Early-Earth Processes

During its first few hundred million years of existence, a great deal happened to the Earth that had a strong bearing on the Earth system in which we live today. It was during this period that the Earth acquired its bulk composition and became segregated into its major subsystems: core, mantle, lithosphere, hydrosphere, biosphere, and atmosphere. These components still bear the compositional imprint imposed at the earliest evolutionary stages, and our concepts of their current dynamics must therefore take into account the conditions of their formation. Thus, in order to understand the gross nature of the Earth system—and especially the interactions among its major components—it is necessary to understand the history of development of these components from the time of the formation of the planetary system until they segregated from one another and began to interact. Because of the antiquity of these events, much of the pertinent evidence is obscure and inferential, with the result that our conceptual models are imprecise. However, precise detail is generally not necessary for the imposition of boundary conditions on current Earth system models.

The earliest significant event in the Earth's history was its formation, together with the other planets, from the primeval solar nebula. The physico-chemical conditions of this collapse produced an immediate segregation of the terrestrial planets from the giant gaseous planets. If we look in somewhat greater detail, we perceive chemical and isotopic differences among the planets, and we must distinguish the differences present initially from those that arose during subsequent early planetary evolution. Physical models of the collapse of the solar nebula and planetary formation are developed by stellar astronomers and planetologists by analogy with other stellar systems, with the aid of chemical, isotopic, and petrologic data from meteorites. Among the important questions relating to the early formation of the Earth are the rate of collapse and aggregation of the planet, which determined the temperature of formation. This is a key issue, because on it hinge other questions pertaining to the volatilization of the incoming materials, early atmospheric development, and the state of oxidation at the surface. It also involves the development of the core, which must have occurred at the earliest stages of the Earth's evolution, and the initial chemical segregation of the planet.

Figure 3.1 SIMPLIFIED CONCEPTUAL MODEL of Earth system processes operating on timescales of thousands to millions of years.



The origin of the moon is intimately related to the question of the early segregation and subsequent development of the Earth. Was the moon blown off the Earth? If the moon formed from the Earth, to what degree did it carry off less dense (and perhaps volatile) materials with it? Obviously, lunar and planetary explorations have been, and will continue to be, instrumental in answering these questions, which are vital to understanding the Earth system.

Geochemical studies have shown that much of the material of the continents segregated from mantle materials during this early stage of terrestrial evolution (Figure 3.3), but over how long a time is a question related to the degree to which this segregation is happening now—an active area of research. How has the chemical and physical development of the continents changed with time? Conversely, what were the extents of the early ocean basins? How did they form?

These questions are clearly related to the last major topic of early-Earth history: the formation of the atmosphere, hydrosphere, and biosphere. Over the past few decades, it has been established that these components also are quite ancient; evidence of their existence may be traced back to 3.8 Ga. We know, of course, that the biosphere has evolved, but to what degree have the atmosphere and hydrosphere changed with time? How, indeed, were these two components generated from the earlier condensed materials that formed the Earth? Are primordial volatiles still being generated from the mantle to act as buffers in our present-day atmosphere and hydrosphere? These are among the fascinating and important questions that must be answered before we can begin to understand the Earth system.

STROMATOLITES AND THEIR ROLE IN ATMOSPHERIC COMPOSITION

At its earliest stage of formation, the Earth was probably surrounded by a gaseous envelope enriched in hydrogen. Planetary scientists generally believe that this initial envelope dissipated rapidly and was soon supplanted by an atmosphere dominated by nitrogen and carbon dioxide, resembling the carbon dioxide-dominated atmospheres of Venus and Mars today. How was this early, large concentration of carbon dioxide diminished to the small fraction (0.03%) now observed? And what mechanism produced the large amount (20%) of free molecular oxygen—a highly reactive gas—now present?

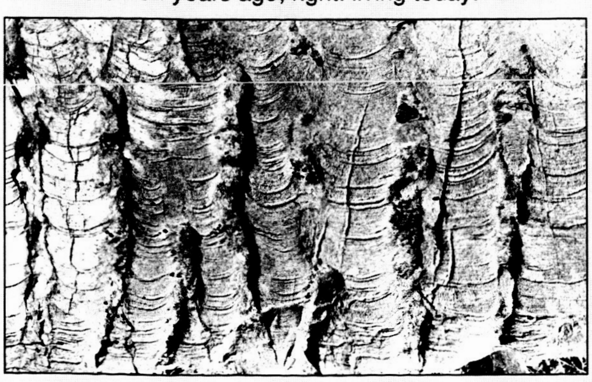
Biological organisms, such as algae and blue-green bacteria, are thought to have played a dominant role in differentiating the atmosphere of the Earth from the atmospheres of its sister planets. The presence of algae—unicellular aquatic plants which, through photosynthesis, take in carbon dioxide and release oxygen—has been traced back some 3.5 billion years in the fossil record, and limestones in the oldest of rocks may well have been algal in origin.

Stromatolites are layered, calcareous structures found in old, sedimentary rocks; they have long been thought to be the products of shallow marine biological processes. These structures have apparently been produced by matlike colonies of algae over much of the history of life on Earth. However, it was not until 1961 that detailed studies of modern stromatolites in Shark Bay, Australia, showed that the biological processes responsible for fossil stromatolites are still at work today (Figure 3.2). More recent research has identified nine constituent types of microbial communities, each forming a characteristic, gumlike microbial mat and calcareous stromatolite. The stromatolite layers form periodically, primarily during the austral summer, as inorganic debris settles upon and is trapped by the mat. A layered, lithified structure is thus built up, to be colonized anew by successive generations of organisms.

In 1935, A.M. Macgregor, a pioneer of African geology, noted a similarity between fossil stromatolites and domelike, sedimentary structures exposed in a limestone quarry near Bulawayo, Zimbabwe. But it was not until the 1950s that the great age of these limestones, now placed at 2.8 billion years, was established. More recently discovered algal colonies in western Australia have been dated to 3.5 billion years ago.

It is therefore plausible to suppose that stromatolite-building algal colonies have existed for at least than 3.5 billion years, and probably longer—acting continuously, in conjunction with more recently evolved aquatic and land plants, to remove carbon dioxide from the Earth's atmosphere and to serve as its source of molecular oxygen. Modern stromatolites have, moreover, provided us with contemporary insights into the earliest biological processes responsible for alteration of the Earth's atmospheric composition.

Figure 3.2 STROMATOLITES. These shallow-water constructions are produced by colonies of algae that have helped shape the composition of the Earth's atmosphere. Examples from western Australia—left: fossils from 3.5 billion years ago; right: living today.



3.A.2. Core and Mantle Processes

The Earth's solid mantle and lithosphere are in contact with three geophysical fluids: air over the continents, water in the ocean basins, and a molten iron alloy at the core-mantle boundary. Because the core begins at a depth just under halfway to the geocenter, it is too remote to interact directly with the geosphere-biosphere, yet it profoundly influences the Earth's other components in a variety of ways traceable to two physical properties of the core: its dynamo-produced magnetic field, and its reservoir of heat. The magnetic field passes readily through the mantle and out into the oceans, atmosphere, and beyond (Figure 3.4). Dynamo action demands vertical upwelling and downwelling of core fluid, so the heat flux delivered by the core into the lower mantle is partly convective and partly conductive in origin.

The Core

The core influences the mantle in two direct ways of importance: it provides heat to the base of the mantle, and it exerts a mechanical torque on the mantle. The former may drive thermal convection in the deep mantle, and the latter influences the length of day (Figure 3.5) and the orientation of the Earth's rotation axis in space. Elucidation of the fundamental mechanisms that govern these two processes motivates the central goals for research on core dynamics as part of the larger Earth system.

Although it is widely accepted that the Earth's magnetic field is maintained against ohmic decay by self-excited dynamo action in the liquid outer core, the details of the process remain obscure. The physical mechanism that produces the fluid kinetic energy converted into magnetic energy by the dynamo, and the depth (or range of depths) in the core at which the source is concentrated, are poorly understood.

Are we witnessing the results of thermal convection driven by radioactive heating distributed throughout the outer core? Is there slurry convection near the top of the core, or is there chemical convection being driven by compositional change and latent-heat release at the boundary between the liquid outer core and the more solid inner core? Can the core magnetic field really change globally within two years, as appears to have been the case during the "geomagnetic impulse" of 1969-1970? Are such events rare or common, and how pronounced can they be? Why does the non dipole field drift to the west at the (slow) rate of about 0.2° of longitude per year?

Probing magnetically more deeply and directly into the fluid core to answer these questions does not yet appear to be feasible, but the construction of "synoptic weather maps" for the movement of fluid near the core-mantle boundary is technically realizable, given adequate data and the satisfaction of appropriate modeling assumptions. The pattern of that motion could reveal the nature of core convection and help to determine the strength of the toroidal field. These fluid mo-

Figure 3.3 SILICA FRACTIONATION distinguishes the components of the solid Earth and provides clues to early-Earth history.

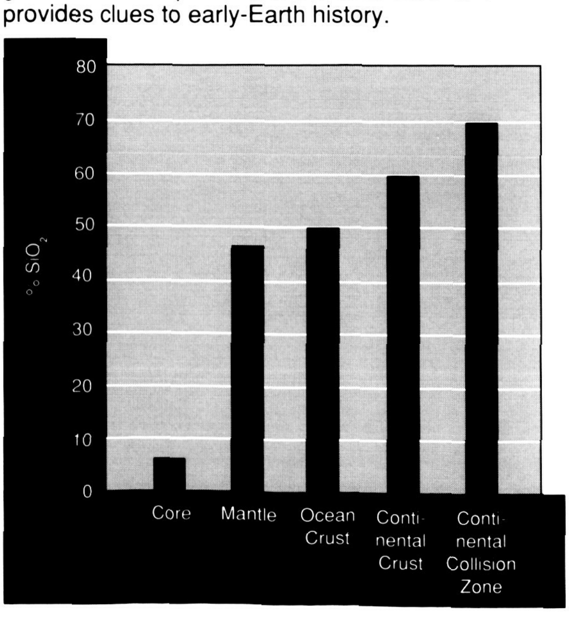
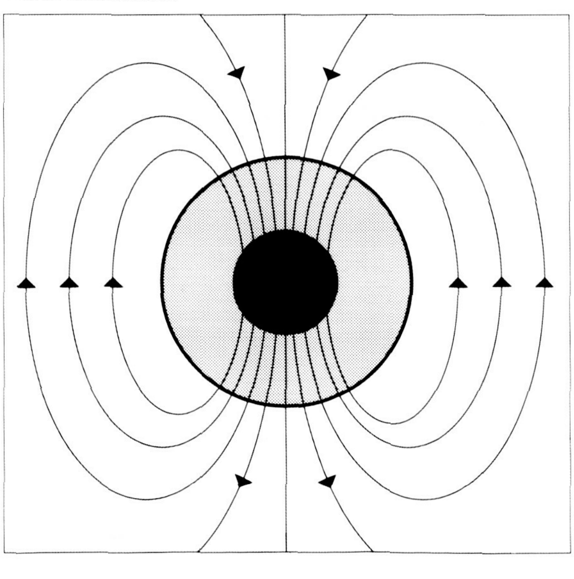


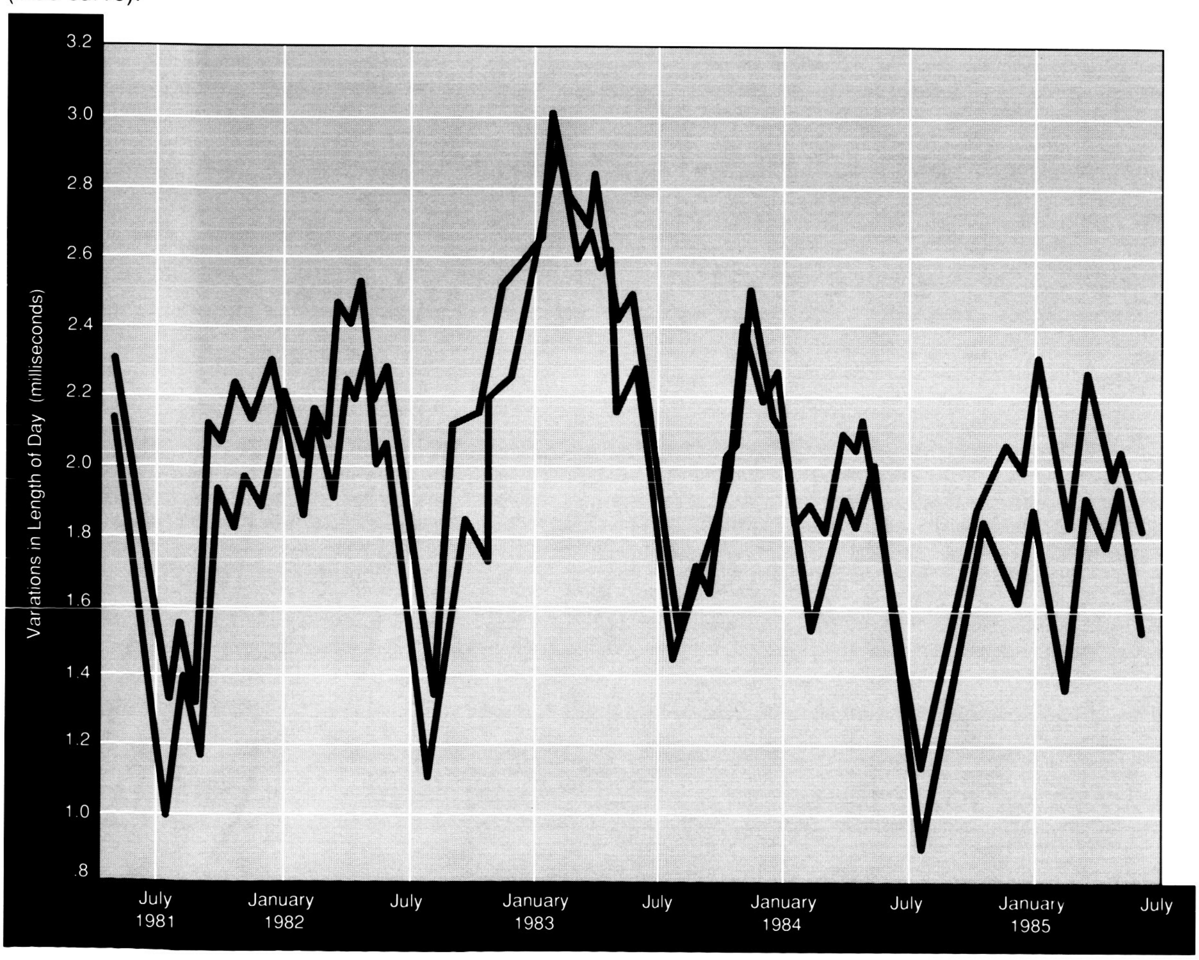
Figure 3.4 THE EARTH'S MAGNETIC FIELD, maintained by dynamo processes in the core, resembles the field of a magnetic dipole at near-Earth distances.



tions move the footprints of the magnetic-field lines as they traverse the mantle and thus give rise to magnetic secular variation. Furthermore, the horizontal divergence and convergence of the flow reveals the sites and intensities of upwellings and downwellings just beneath the core-mantle boundary—information required for estimates of the convective heat flux ultimately delivered into the base of the mantle. It will be especially important to see whether there is a long-term imprint of the Earth's rotation on the convective heat flux reaching the top of the core, some part of which presumably also reaches the Earth's surface.

Currently, the major scientific challenge facing the subject of core fluid dynamics is to develop sound methods for extracting a description of horizontal fluid motions near the top of the core from magnetic measurements taken at and above the Earth's surface. Such methods could be implemented with observations made at different epochs, thereby providing information on the time-dependence of the motion and its fluctuation timescale. Determination of the convective and conductive heat fluxes from the deep core would then follow in comparatively straightforward fashion, aided by present estimates of the adiabatic temperature gradient at the surface of the core and assumptions about the vertical scale heights of temperature variations and vertical motion. Crustal magnetic-anomaly mapping has increased substantially in coverage, resolving power, and accuracy because of incorporation of data returned by the Magnetic Field Satellite (Magsat) in 1980. The vertical magnetic field at the core-mantle boundary has been shown to be only moderately affected by mantle conduction, and magnetic impulses there can be viewed as inputs to a filter—the mantle—whose measured response contains limited but valuable information on mantle time constants and conductivity.

Figure 3.5 VARIATIONS IN THE LENGTH OF DAY arise from a variety of Earth system processes, including a mechanical core-mantle interaction and motions of the atmosphere. The importance of atmospheric effects is demonstrated by the close correlation of direct measurements by Very Long Baseline Interferometry (black curve) and variations inferred from changes in angular momentum of the atmosphere (blue curve).



Seismic waves provide sensitive probes of inner-Earth structure (Figure 3.6). Seismic-tomography studies of the lower mantle indicate the existence of mantle density variations that are matched by long-wavelength features of the geoid and that imply kilometer-scale relief at the core-mantle boundary. This relief may play a controlling role in core-dynamo mechanics, and its movement may control such phenomena as the westward drift of the geomagnetic field and changes in the length of day. Tomography can potentially be used to observe density or chemical variations of the fluid outer core and solid inner core. Such observations will contribute to an understanding of the thermal behavior of the core, chemical differentiation, and operation of the magnetic dynamo.

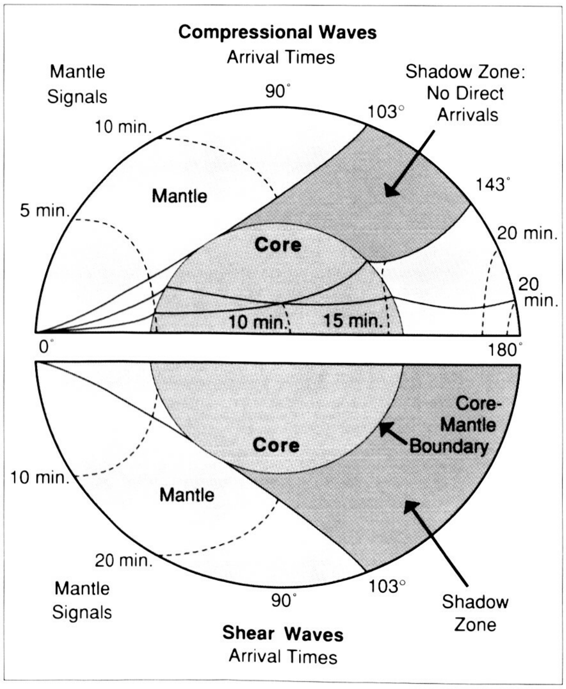
The Mantle

Understanding the nature of (and relations among) heat transport, convective flow, chemical differentiation, and remixing in the mantle is central to knowledge of how the Earth system works and how it has evolved over geologic time. Variations in mantle density may reflect temperature or compositional variations, or differences in state caused by partial melting, giving rise to perturbations in the gravity field and stresses that would cause deformation and flow. Seismic observations of heterogeneities have confirmed our view that some sort of density-driven flow transports heat and moves material in the mantle over timescales ranging from tens to hundreds of millions of years. But beyond this extremely general conclusion, our knowledge of just what these anomalies represent, and their relation to flow and transport processes, is still vague. Basic questions remain: Do the seismic results imply variations in temperature or in composition? How much heat transport is associated with the observed patterns? Does thermal convection efficiently remix the products of differentiation in the mantle?

The vertical extent of convective flow in the mantle is still a major question. The flow may be confined to layers by chemical stratification, the separate layers providing relatively isolated chemical or isotopic reservoirs that can be identified through geochemical observations and modeling. The stability of layered convective systems depends on the relative magnitudes of thermal and compositional density variations; the magnitudes of these variations, and their relation to specific materials, must be determined and the conditions for stability in, and mixing processes between, reservoirs must be elucidated. The conditions for different patterns and rates of flow must be known in three dimensions in order to interpret the observations of mantle flow.

The rheology of the mantle—the relation between stress and deformation—provides the link between the driving forces causing flow and the rates of flow and deformation. The variation of rheology with depth, together with its dependence on stress, pressure, temperature, composition, and state, govern the rates and patterns of flow and the magnitude of forces causing tectonic deformation on the surface. The rheology of the mantle can be measured directly by observing current deformation rates. It can also be inferred from models of flow or plate motion, or it may be predicted from laboratory measurements and understanding of the physics of plastic deformation of solids. Direct observations, simply because they are direct, are most valuable. Presently, there are only a few observations of postglacial rebound rates, polar wander and rotational acceleration, and temporal changes in the gravity field. Extended-area measurement of postglacial rebound at some distances from shorelines can greatly improve the understanding of the rheology of the upper mantle, while measurements of changes in lower-order components of the gravity field will determine the lower-mantle rheology and its structure with depth.

Figure 3.6 SEISMIC WAVES radiating from an earthquake epicenter reveal inner-Earth structure. The Earth's core blocks transmission of shear waves (lower shadow zone) but acts as a lens to focus compressional waves onto the far side of the Earth (upper shadow zone and mantle signals).



Seismic tomography is improving our understanding of the three-dimensional seismic structure of the body of the Earth, but these data must be combined with high-quality observations of the gravity field to achieve the next level of understanding of mantle dynamics. To do this, an improved seismic network and more accurate global satellite gravity-field data are required. Additional satellite-derived data on the time-varying gravity field are needed to help define the global rheology of the mantle. These data should be coupled with laboratory studies of the solid-state geophysics of candidate mantle materials and corresponding numerical modeling.

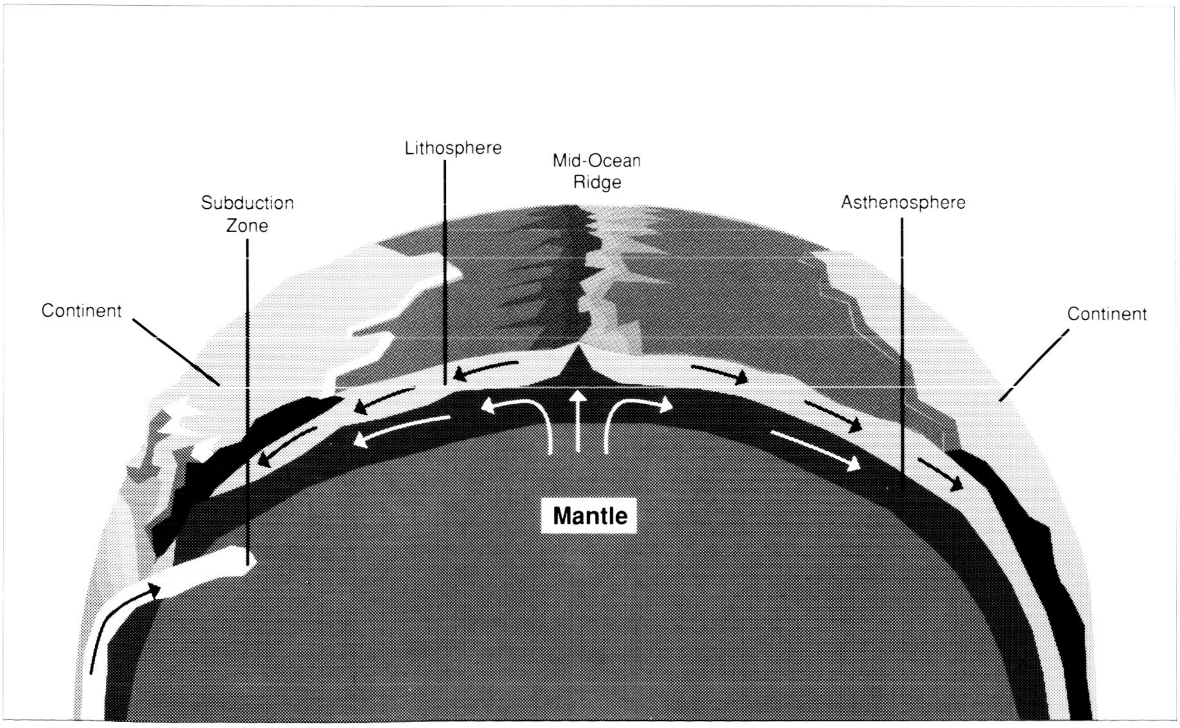
It is useful to view global dynamics as the interplay between two different kinds of driving forces: body forces, caused by density changes resulting from differences in temperature or composition; and resisting forces, resulting from the resistance of Earth materials to deformation. This deformation leads to a redistribution of stress within the Earth, leading to further deformations, future redistribution of stress, and so on. In order to understand global dynamics, we need to observe these deformations on a wide range of timescales. In short, we want to know how the density contrasts of convective origin (million-year timescales) drive the surface plates, leading to great earthquakes that occur over a time span of seconds at intervals on the order of a century.

Questions that must be answered along the way include: What is the distribution of body forces driving mantle convection? What are the accompanying changes in temperature, phase, or composition? What are the rheological properties of Earth materials? How do they change on the relevant timescales (seconds to millions of years)? What are the vertical and horizontal motions of the Earth's surface? How do they vary with position and with time? What are the motions of the Earth's interior? How are they coupled to crustal motions at the surface? These questions must be addressed through a combination of observations, laboratory experiments, theory, and numerical experiments.

3.A.3. Plate Tectonics

The theory of plate tectonics has led to a dramatic increase in our understanding of a wide variety of geologic processes. According to this theory, the Earth's surface may be divided into a number of quasi-rigid plates in continuous relative motion. The continents are distinct from the marine plates, which are created by the upwelling and cooling of lava from the mantle at oceanic spreading centers and ultimately destroyed through subduction back

Figure 3.7 SCHEMATIC VIEW OF PLATE-TECTONIC PROCESSES. The terms *asthenosphere* and *lithosphere* are used to distinguish mechanically between the bulk of the mantle that deforms by convective flow and an uppermost region that, together with the overlying crust, behaves rigidly under normal conditions.



into the mantle at convergent plate boundaries. This global geophysical process gives rise to the great majority of earthquakes and volcanoes at the boundaries between plates and, over extended periods of geologic time, to the formation of ocean basins and mountain belts (Figure 3.7). An additional consequence of plate tectonics is the epochal connection or isolation of continental land masses (e.g., the Caribbean land bridge: Figure 3.8), with important implications for the migration and evolution of biological species.

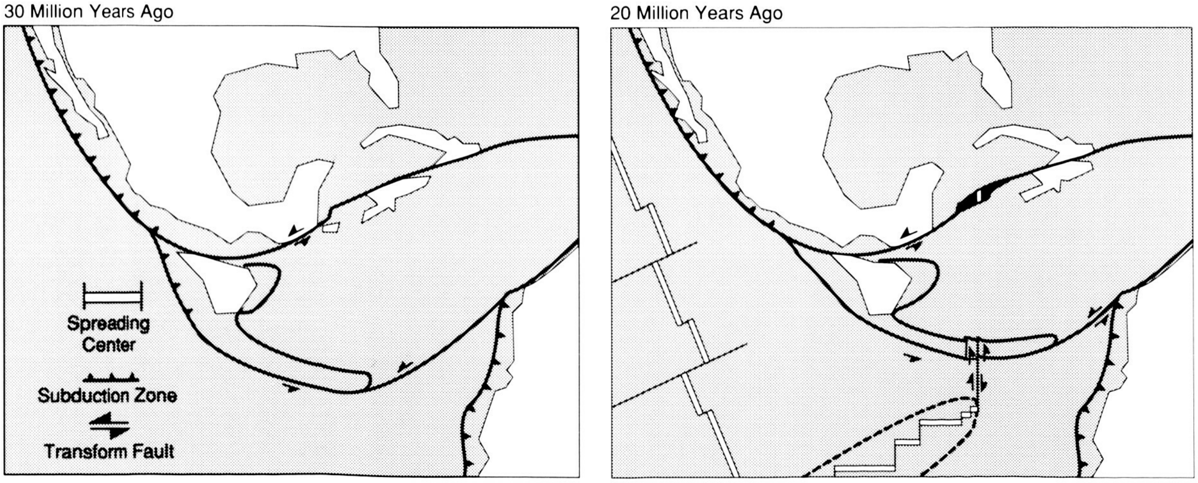
The rates at which the plates move relative to one another vary and range from 0 to 20 cm/year. Time-averaged rates of plate motions can be obtained indirectly from magnetic anomalies on the sea floor and the record of polarity reversals of the Earth's dipole magnetic field. However, these are averages of rates over the last few million years, and, as evidenced by earthquakes, movement is actually episodic, at least at plate boundaries. It is only within the last several years that, through the use of satellite technology, contemporary rates of relative plate motion have been measured directly. This achievement raises the possibility of assessing the time-varying rate of movement. This rate, determined as a function of distance from the plate boundary, will be important to the development of models of the rheology of the lithosphere.

A prime requirement for an understanding of global tectonic processes is the direct measurement of the present rates of motion between the stable portions of the Earth's tectonic plates. We must test whether short-term and long-term rates of plate motion are equal. It is also important to determine the length scale over which episodic slip at plate boundaries is damped out to produce steady motions.

A major earthquake is generally followed by deformation in the region lasting over periods of years. This postseismic deformation is related to the viscous properties of the crust and mantle but has not been determined except in restricted regions in the cases of a few large earthquakes along plate boundaries. An important goal, therefore, is the measurement of time-dependent deformation in a number of the major worldwide seismic zones in order to address the question of coupling between motions in the mantle and deformation in the crust. We wish to learn how stress and strain are distributed across major fault zones as a function of lithosphere type (continental or oceanic) and structure, and even across such zones on the ocean floor. Of specific interest is the postseismic horizontal and vertical deformation following a large plate-boundary earthquake and its relationship to the rheological structure of the lithosphere and the underlying upper mantle.

Models of the generation of great earthquakes resulting from the unsticking of locked segments of the boundaries of moving plates are successful at predicting the known approximate recurrence intervals of about 100 years. The more detailed knowledge required to make specific predictions of the timing and location of these episodes requires a better understanding of prefailure processes. Any such deterministic model will depend heavily on *in situ* measurements of physical properties and patterns of strain accumulation. Given that great earthquakes involve rupture over several hundred kilometers, and are thus likely to be associated with perturbations in the strain field over greater distances and time spans ranging from days to decades, the fundamental observations required are changes in the strain field over scales ranging from

Figure 3.8 EVOLUTION OF CARIBBEAN LAND BRIDGE through plate-tectonic processes over the past 30 million years.



meters to hundreds of kilometers. It is vital to the understanding of this problem that long-term satellite observations of the plate-boundary deformations near major seismic gaps be undertaken soon to provide a record of sufficient length to help in the modeling effort. As in other disciplines, observations are the key to model development and testing.

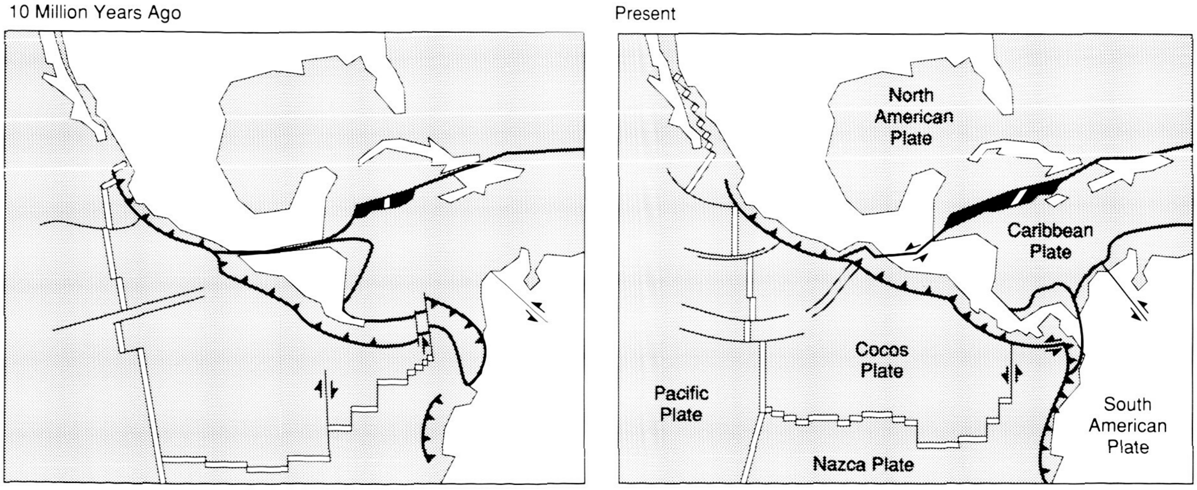
A related goal is an understanding of the earthquake cycle (Figure 3.10) and its relation to stress, strain rate, fault structure, and the conditions under which major earthquakes display diagnostic precursory phenomena. While the ability to predict earthquakes has remained an elusive goal for more than two decades, progress is steady, and it can be anticipated that both geodetic and seismic measurements will play important roles.

The continents, composed of lighter rock floating on the denser mantle below, are assembled and reassembled over timescales much longer than those characterizing crustal generation. Much of the existing continental crust, at least that created since Archaean times, appears to have formed in an island-arc environment. Island arcs, deep-sea trenches, and back-arc basins form a tectonic system that marks the consumption of oceanic lithosphere at subduction zones (see Figure 3.7). To understand the formation of continents, a number of fundamental questions concerning plate-boundary tectonics must be answered. For example: What is the nature of arc evolution? What are the dynamics of mountain building at convergent boundaries, including thrust faulting that accompanies ocean-continent plate convergence and continental collisions? What is the growth of continental crust with time?

The deformation of plate interiors is also a poorly understood process in solid-Earth dynamics. Large areas of continents have been slowly uplifted as broad plateaus, while others have subsided to become intracontinental basins. The origin of these slow but long-continuing vertical movements within plates, and their relationship, if any, to forces at plate boundaries, are not generally understood.

Rifts—elongated depressions overlying places where the lithosphere has ruptured in extension—are a fundamental tectonic feature of the Earth's surface; however, we know very little about the dynamics of rifting. What causes the onset of rifting of continental crust? What are the important factors determining why some rifts "fail" (i.e., cease rifting), while others "succeed" and evolve into oceans? What are the mechanics and timing of igneous activity in rifts, and to what extent does this activity influence rift evolution? The answers to these questions are unknown.

We are similarly ignorant of the processes that give rise to continental plateaus. We need to measure the rates of uplift and extension and to determine the states of stress and strain. Dynamic models for plateau uplift must be tested against improved thermal, seismic, and potential field data. Flexure of the lithosphere as it responds to geologic loads (e.g., volcanic islands) provides information on the mechanical properties of the Earth's lithosphere. Such studies should be extended to determine the differences between continental and oceanic lithosphere and to measure any viscous components in the rheology of the upper lithosphere. Determination of the peripheral uplift or subsidence pattern in areas of recent deglaciation and in coastal regions would permit an improved determination of the radial viscosity profile in the Earth's mantle and an estimation of lateral variations in mantle viscosity.



EVIDENCE FOR PLATE TECTONICS

Detailed mapping of the Atlantic Ocean basin and its continental coasts began with voyages of discovery in the late 15th and early 16th centuries. The striking congruence of the western African and eastern South American coastlines did not escape early notice; however, no one could explain how the continents, if united in the past, could migrate through the Earth's crust to global separations. There the matter rested until early in the present century, when F.B. Taylor and Alfred Wegener revived the theory of continental drift, but without offering a credible mechanism for such motions.

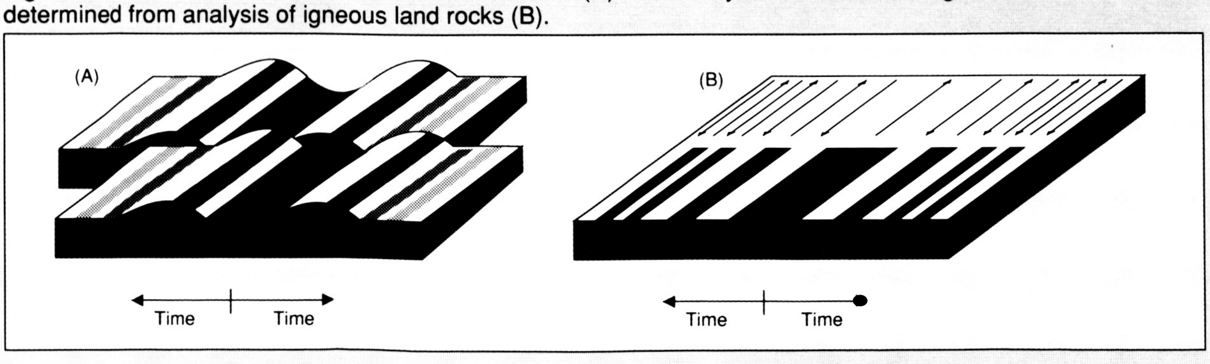
A new period of investigation began following the technological advances of World War II and organization of the International Geophysical Year (IGY) in 1957-58. The IGY promoted a series of expeditions to map the ocean floor and the enhancement of a worldwide seismic network, which has since been greatly enlarged. There followed, during the late 1950s and early 1960s, a number of discoveries that profoundly changed our view of Earth evolution over geologic timescales.

One of the first and most intriguing of these discoveries was the presence of alternating magnetic patterns in rocks on the sea floor, which were found to follow the offsets of numerous transverse faults (Figure 3.9, A). Concurrently, systematic exploration of the Atlantic Ocean floor revealed the great mid-Atlantic rift; extensions of this work to other ocean basins produced the first detailed global relief maps of the sea floor and documented the existence of a worldwide ocean rift system. Rocks dredged from the sea floor were found to be nowhere more than 200 million years old, and deep sediment cores confirmed the comparative youth of the present ocean bottom in geological time.

Field studies of the direction of magnetization of dated lava flows showed that the Earth's magnetic field periodically reverses direction and therefore imprints a "magnetic clock" in newly solidified igneous rocks (Figure 3.9, B). Ocean surveys revealed that stripes of alternating magnetic polarity on the ocean floor are symmetrical about ocean rifts. It was then realized that the ocean-floor magnetic-stripe patterns are correlated with the magnetic reversal clock, thus lending credence to the hypothesis of sea-floor spreading as a source of new oceanic crust. Meanwhile, accumulated seismic evidence was demonstrating that the epicenters of deep earthquakes are invariably associated with the global rift system, marking the rifts as major sites of geophysical activity. Later investigations of rift features by deep-submersible craft, which discovered pillow lavas and "black smoker" hydrothermal vents, have confirmed this view.

By the mid-1960s, these strands of evidence had been united into the currently accepted picture of plate tectonics. The Earth's crust consists of enormous plates, born at mid-ocean ridges, floating upon the convective mantle of the Earth. These plates push against, slide by, or descend under neighboring plates until they ultimately are subducted back into the Earth's interior along convergent plate boundaries. Plate subduction thereby explains the existence of deep ocean trenches, all of which have similar depths; patterns of volcanism, mountain building, and earthquake activity all fit consistently into this new view.

Figure 3.9 MAGNETIC PATTERNS in sea-floor rocks (A) are closely correlated with magnetic reversals determined from analysis of igneous land rocks (B).



Models currently describe mantle heating as being due largely to the decay of radioactive elements, and the partial melting of ascending material to form magma as due to decompression. At various stages, melt is extracted (sometimes less than 1% of the partially molten slurry), the beginning of a phenomenon that results in the great diversity of rock types at the Earth's surface. The magma ascends by various mechanisms (Figure 3.11), depending largely on tectonic setting, and is often released through submarine or subaerial volcanic eruptions. It may also crystallize beneath the surface. In the latter case, partial crystallization may result in further fractionation and the formation of exotic rock types and mineral deposits. It may also lead to the segregation of a gas phase which, if temporarily trapped, can produce a substantial release of energy, as in the case of the Mt. St. Helens eruption in 1980.

However, our models are far from complete, and insight into the process of magmatism and related phenomena ranging from the formation of the crust to the formation of mineral deposits will require deeper knowledge of the process of magma generation than we now possess. In order to understand these processes, the following major goals should be achieved:

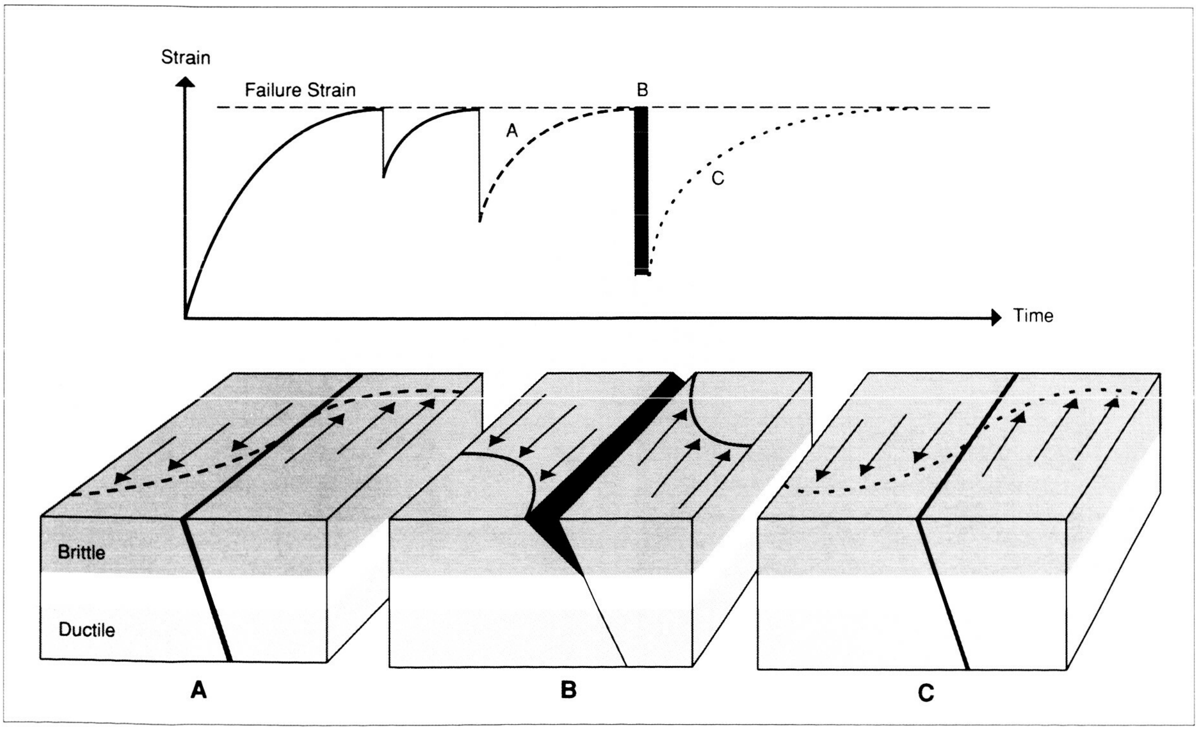
- Quantitative definition of the location, character, and origin of chemically distinct reservoirs within the Earth. It has recently been established that the mantle is chemically heterogeneous—an important fact relating to the history of fractionation of the Earth and the variable composition of the crust. This effort is directly related to the discovery and description of geophysical heterogeneities, such as those defined by gravity, geoid, and body-wave tomographic studies.

- Development of a quantitative understanding of magmatism and geochemical cycles at continental margins. The growth of continents through accretion at their margins ranks as the most important and obvious manifestation of the continued differentiation of the planet.

- Deeper understanding of the physics and chemistry of magma generation. Realistic models based on experimental and observational evidence will permit extrapolation to a wide range of tectonic settings and yield insight into the structure of the mantle and the process of crustal evolution.

- Documentation of the role of material diffusion (metasomatism) in the evolution of the crust-mantle system. Much evidence points to

Figure 3.10 THE EARTHQUAKE CYCLE. The buildup of strain (A) is suddenly released in displacements along a fault zone (B), followed by strain reaccumulation (C).



the importance of the mantle metasomatism, through which material is transported by fluids diffusing slowly along grain boundaries, but little is known about the composition or origin of these fluids.

• Determination of volatile budgets and cycling among the Earth's interior and its crust, atmosphere, and hydrosphere. The results of experimental and analytical investigations into the origin and distribution of volatiles within the planet can help reveal the extent to which mantle volatiles are recycled or juvenile, as well as the origin and evolution of the atmosphere and oceans and the extent to which they can buffer anthropogenic changes.

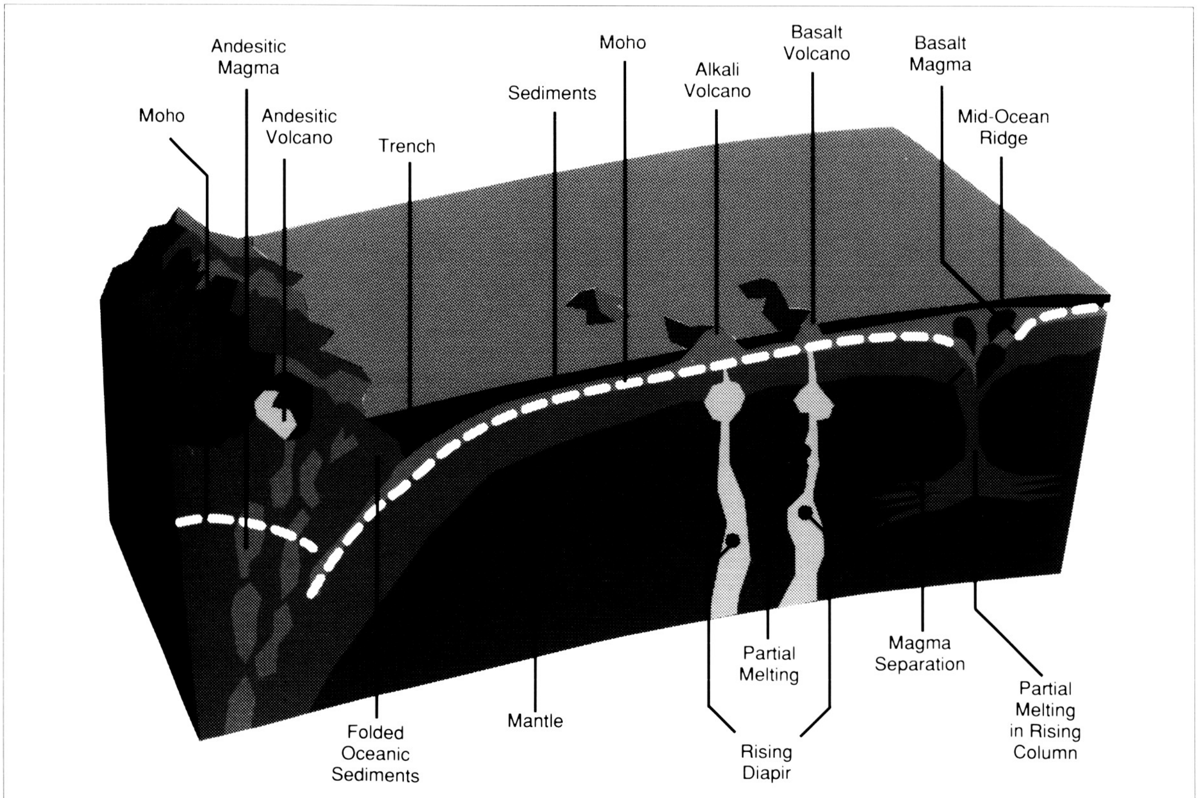
• Determination of the effects of volcanism on global climate. Since major eruptions (e.g., Krakatoa in 1883) are known to influence global climate for years afterward, climate models must include the capability of predicting the occurrence and nature of major volcanic eruptions.

3.A.4. Solar-Driven Processes

The sedimentary rocks that cover most of the solid Earth contain our most complete and millions of years. This record embodies not only the history of the crust but also chronicles events affecting the Earth's flora and fauna, its atmosphere and oceans, and its climate. A canyon in Africa, a road cut in Pennsylvania, a fjord in Greenland—any significant section of sedimentary rocks—attests to great changes: from simple organisms to complex, from coal deposits formed in tropical swamps to conglomerates formed at the mountains' edges to limestones formed in the deeper oceans. These are the records of solar-driven erosion and deposition and of changes in the atmosphere and the oceans.

Understanding the origin and evolution of sedimentary basins is critical to questions as diverse as petroleum formation, aquifer storage and transmission, and waste disposal. What interplay of tectonic forces gives rise to these basins and their continued development? What are the pressures and temperatures of the chemical regimes for the compaction and diagenesis of sediments and the metamorphism of hydrocarbons in these basins? How do fluids migrate in a basin as sediments accumulate? What is the rate of subsidence as basins become filled with sediment? These are among the most important questions facing geologists today.

Figure 3.11 MAGMATIC PROCESSES on land and beneath the ocean floor. Magmas are released through sea-floor spreading and volcanic eruptions. The Mohorovicic discontinuity (Moho) marks the compositional boundary between the crust and the mantle.



One of the most spectacular results of the dynamic behavior of the Earth's interior is the generation of topography in broad uplifts on the land, in the development of basins in the oceans, and in the construction of mountain belts. Topography exerts a major influence on erosion and the subsequent deposition of sedimentary rocks.The size and sorting and the physical and chemical compositions of sedimentary deposits are similarly related to topography. As topography changes in response to the dynamics of the mantle and the overlying plates, so does the nature of sedimentation.

In the context of global patterns of climate and vegetation, the formation and development of soils, including their depths and types, are influenced by topography, as is the nature of weathering (mechanical or chemical) and, thus, the chemistry of soil formation (Figure 3.12). Topography affects these surface processes in another, more subtle, way through its influence on climate (e.g., mountain glaciation producing moraine deposits, lee deserts producing loess, and rain forests producing lateritic soils; see Figure 3.13). In order to understand such processes and their interactions, it will be necessary to study the relationships among geomorphology, climate, and sedimentology both in contemporary settings and in the geological past. The relatively complete Quaternary record of erosion and deposition, within which the influence of Milankovitch cycles has been clearly discerned, is beginning to yield a fascinating story of complex interactions and nonlinear responses, of which the postglacial recovery of atmospheric CO_2 is the most familiar. The implications of the complexity of these responses for models of the Earth system on short timescales have yet to be fully realized. In particular, the pattern of soil structure and nutrient content is a critical heritage for contemporary ecosystems. Soil formation and evolution take place over many thousands of years, and understanding soil conditions worldwide (Figure 3.13) is a prerequisite to understanding their modification by human activities.

The dynamics of the processes by which the Earth's surface features were formed are not sufficiently understood (for example, in tropical and desert environments), and our understanding of the past needs to be improved through the study of modern analogues. Through such investigations, it may become possible to extrapolate to conditions very early in the Earth's history when these erosional and sedimentary processes took place without interaction with the biosphere and in a more reducing environment. These studies are also required for forecasts of the effects of human activity, such as urban development, deforestation, and (nuclear) waste disposal. Scientific observations of great floods, ice advances, sea-level changes, and volcanic eruptions are both short and incomplete. However, the longer time spans represented, for example, by ancient flood, glacial, and coastal deposits provide the missing perspective.

Our understanding of geochemical cycles requires knowledge both of the erosional and sedimentary parts of these cycles. Until the last few decades, we did not have sufficient data on global rates of erosion, transport, and sedimentation to make great progress, but modern research has permitted the construction of geochemical models for cycling of the elements—especially carbon, nitrogen, phosphorus, and sulfur—that have underscored the importance of biogeochemical cycles in the Earth system. Further work is needed to detail the locations and extent of reservoirs for these and other biogeochemically critical elements, as well as the physico-chemical sensitivities of the fluxes among their reservoirs.

3.A.5. International Programs and Coordination

The principal international coordinating organization for geology and solid-Earth geophysics is the Inter-Union Commission on the Lithosphere (ICL), a permanent commission of the International Council of Scientific Unions (ICSU). Established in 1980 by request of the International Union of Geodesy and Geophysics (IUGG) and the International Union of Geological Sciences (IUGS), ICL is the successor to earlier international bodies associated with the International Geophysical Year (IGY, 1957-1958), the Upper Mantle Project (1960-1970), and the International Geodynamics Project (1970-1980).

The International Lithosphere Programme (ILP) is the research program overseen by ICL. It embraces virtually every aspect of the origin, dynamics, and evolution of the lithosphere: recent plate movement and deformation, interplate phenomena, structure and dynamics of the lithosphere-asthenosphere system, paleoenvironmental evolution of the oceans and atmosphere, environmental geology and geophysics, mineral and energy resources, deep continental drilling, data centers and data exchange, and geosciences in the developing nations. National committees for the ILP have been formed in over 50 countries.

A number of important specific projects are carried out through the ILP. These include deep continental drilling, continental and ocean seismic reflection profiling, electromagnetic sounding of the mantle, and, most recently, the Global Geotransect Project, directed toward a compilation of data taken across boundaries of geodynamical significance and toward the physics and chemistry of Earth materials.

The ICL has also played an important role in the definition and establishment of the International Geosphere-Biosphere Programme (IGBP). Individual ICL representatives participated actively in IGBP planning sessions and supported the ICSU endorsement of IGBP in 1986. The major point of contact between ILP and IGBP is the ICL Working Group on Paleo-Environmental Evolution of the Oceans and Atmosphere, which is concerned with the history of past climatic changes.

Other international efforts directed at the study of global change over longer timescales are mentioned in connection with the specific research areas discussed below.

3.B. REQUIRED OBSERVATIONS AND PROCESS STUDIES

Inferences about the long-term evolution of the Earth system are inevitably somewhat indirect. From the perspective of space, the central themes on these timescales are understanding the mechanisms for plate tectonics, inferring the degree of heterogeneity of the mantle, and unravelling the processes that have led to the present structure of the continents. Also particularly significant for comparative planetology are the origin and secular variations of the Earth's magnetic field.

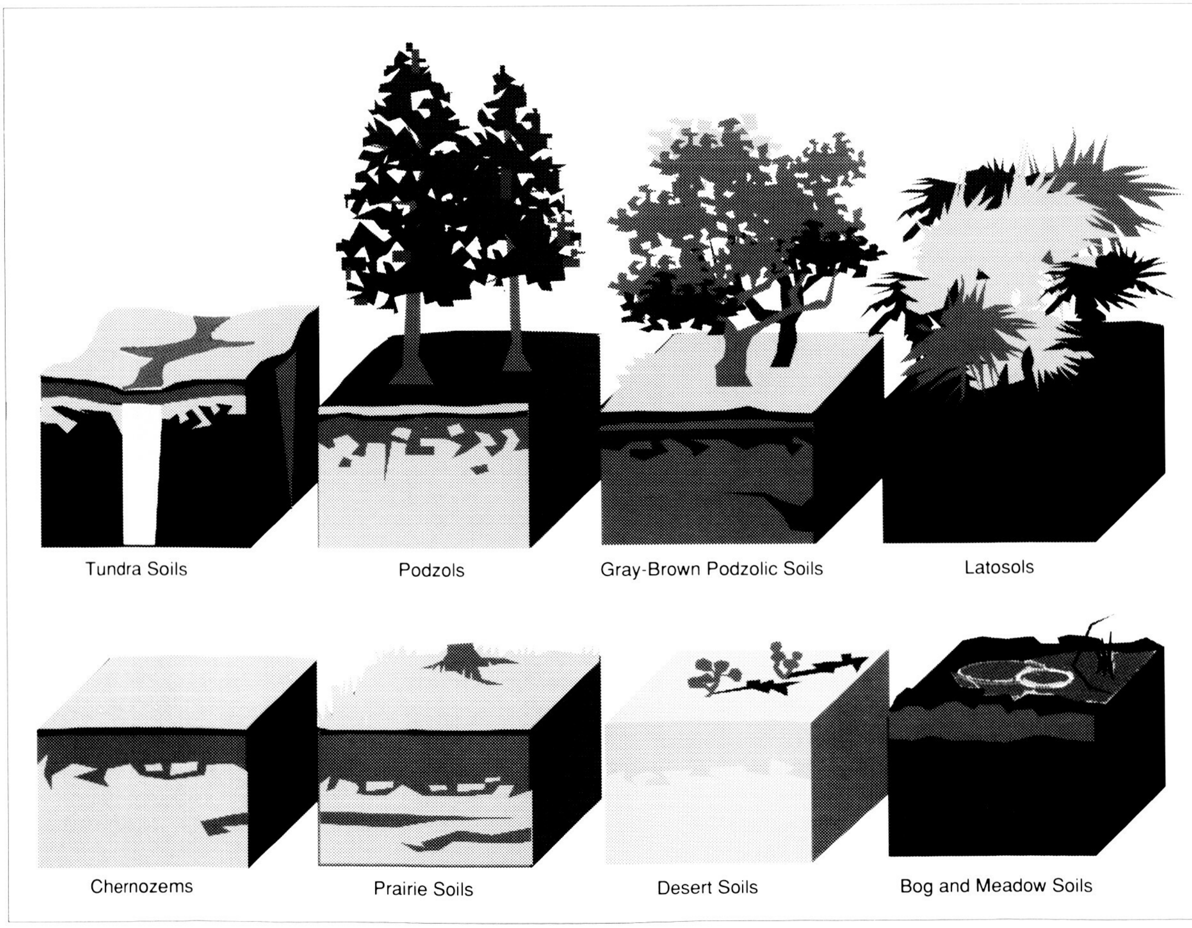
The observations and research required to advance these areas fall into three distinct categories that require different approaches to implementation. They are:

- Sustained, long-term measurements of global geophysical variables, whose rates of change are best found directly from differences measured over the greatest feasible interval of time;

- Observations of global fields that provide a fundamental description of the Earth and its history; and

- Localized case studies of individual proc-

Figure 3.12 SOIL FORMATION. The action of vegetation is an important factor.



esses, which are then extrapolated to assess the impact of these processes on a global scale.

The discussion to follow emphasizes measurements from space, together with the ground-based activities essential to take full advantage of them. Important additional information on the Earth system on these timescales is anticipated from complementary approaches, such as seismic tomography, the study of geochemical tracers, and laboratory studies of the physical and chemical constitution of the mantle and core, which are also under development (see Chapter 7).

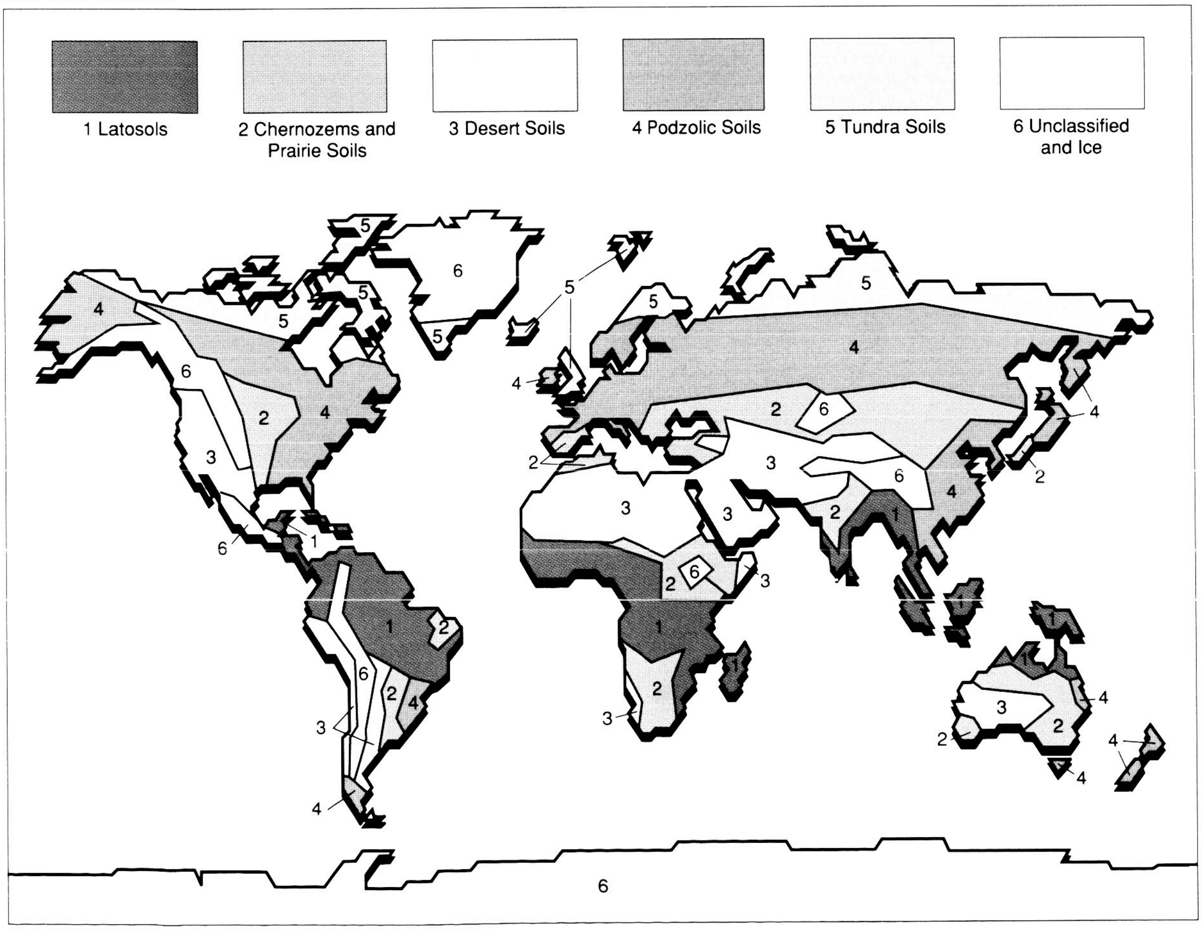
In the first category—changes in global geophysical variables—one needs accurate measurements repeated at intervals, generally for a decade or longer. Data rates tend to be fairly low. The emphasis is on overall measurement precision and sustainability of the measurements over time.

In the second category—observations of global fields—specialized missions are required; if successful, they need to be repeated only if advances in technology or experience permit an order-of-magnitude improvement in accuracy or spatial resolution. Substantial scientific advances generally depend upon integration of the measurements into quantitative models, along with other nonsynchronous data on comparable scales from diverse sources.

With respect to the third category—process studies—the information from satellite observations is generally contained in the patterns revealed by high-resolution images and their qualitative relationship to other data fragments. Close coordination with *in situ* observations and other sources of data is central to effective progress. Data volumes are large, so that efficient data management and geographically based information-retrieval procedures are essential. Because the analysis process tends to be exploratory, involving much subjective judgment and qualitative inference, the extrapolation of experience from localized cases to inferences about entire regions and global impacts will normally be a gradual process requiring extensive image processing, pattern recognition, and computer modeling by highly skilled scientists.

We now turn to the observations important

Figure 3.13 SOIL DEVELOPMENT. Major soil regions (here shown simplified) reflect patterns of past vegetation and climate.



to the study of global change on timescales of thousands to millions of years, and to relevant research foci and process studies, as given in tables 3.1 and 3.2. These tables are abridgements of the more extensive tables 9.1A, 9.1B, and 9.2 of Chapter 9.

3.B.1. Plate Motions

A notable need is the determination of the movement of lithospheric plates relative to each other as a contribution to documenting the processes of plate tectonics. Such determinations are complementary to advances in modeling the mantle and lithospheric structure from maps of gravitational anomalies and the results of seismic tomography. Measurement of plate movement requires extremely precise determinations (within a few centimeters) of position relative to a global frame of reference for a sample of baseline locations around the world, repeated at intervals over a period long enough for the trend to be clearly discernible above instrument noise. The data accumulated over the past decade from tracking the Laser Geodynamics Satellite-1 (LAGEOS-1) and from more recent Very Long Baseline Interferometry (VLBI) reveal interplate motions similar to those that previously could only be estimated from the geologic record as velocities averaged over tens of millions of years. Research emphasis should now shift to zones of tectonic deformation. The key to exploiting this opportunity to yield a completely new perspective on plate motions is to complement these systems by taking advantage of the extraordinary accuracies obtainable over shorter baselines by ground-based receivers

TABLE 3.1

Observations important to the study of global change on timescales of thousands to millions of years.

SUSTAINED, LONG-TERM MEASUREMENTS OF GLOBAL VARIABLES

Variable	Importance	Analysis Product Quality
Geophysical Variables:		
Plate motions	★★	B
Plate deformations (small-scale)	★★★	C-
Polar motion and Earth rotation	★	C
Time-dependent magnetic field	★	B
Changes in gravity	★	C

FUNDAMENTAL DESCRIPTION OF THE EARTH AND ITS HISTORY ON A GLOBAL SCALE

Parameter	Importance	Analysis Product Quality
Land-Surface Data:		
Topography (absolute height)	★★	A-
Surface structure (slope and aspect)	★	C-
Lithology and mineral composition	★★	D-
Surficial deposits and soil maps	★	C-
Geophysical Fields:		
Gravity and geoid	★★★	B-
Global seismic properties	★★★	C-
Crustal magnetism	★	C

NOTE: For further details on table entries, see Chapter 9, tables 9.1A and 9.1B

KEY

Importance (for documenting and understanding global change):

★★★ Essential ★★ High ★ Substantial

Analysis Product Quality (presently available multiyear global analyses):

A = Good quantitative, well calibrated
B = Well discriminated, absolute accuracy doubtful
C = Useful, poor discrimination
D = Qualitative index, interpretation doubtful
F = No information
- = Not global coverage

TABLE 3.2

Examples of near-term research foci and process studies relevant to the study of global change on timescales of thousands to millions of years.

Topic	Name
Early-Earth Processes:	
Comparative planetology and the early Earth	CPEE
Core-Mantle Processes:	
Mantle circulation	Mantle Circulation
Core dynamics and the Earth's dynamo	CDED
Plate-Tectonic Processes:	
Motions and deformations of lithospheric plates	Crustal Dynamics Project
Mechanisms of continental assembly and evolution	Continental Lithosphere
Processes at ocean spreading centers	ORCP
Magmatism and Volcanoes	M&V
Solar-Driven Processes:	
Mechanisms of soil formation and evolution	MSFE

NOTE 1: Many observations are needed for (and justified by) these research foci and process studies in addition to the observations listed in Table 3.1.

NOTE 2: For further details on table entries, see Chapter 9, Table 9.2.

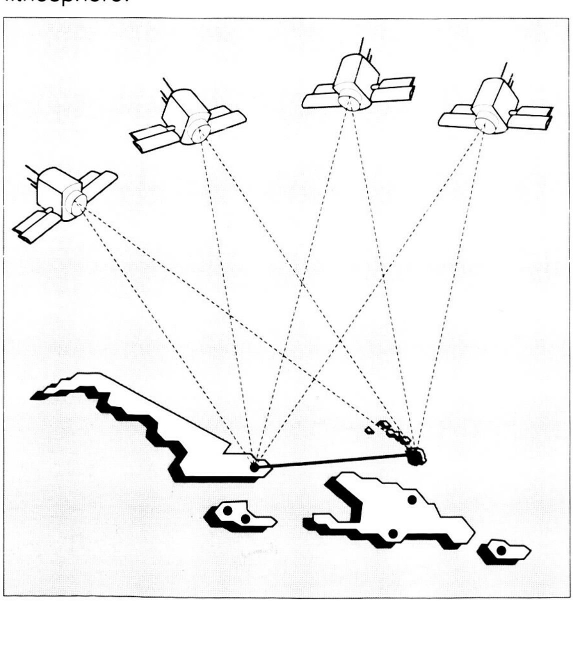
using signals generated by the Global Positioning System (GPS) array of satellites (Figure 3.14). International studies of lithospheric motion are coordinated by the ICL Working Group on Plate Motion and Deformation.

3.B.2. Plate Deformations

The most important goal of the GPS geodetic observations is to reveal the rates of deformation within the continents and across major fault zones at plate boundaries by more abundant observations on shorter baselines. Taken in conjunction with *in situ* strain measurements and geologic surveys, this information is central to understanding the structural evolution of the continents and the processes determining the distribution and timing of earthquakes.

Present capabilities for such research would be greatly enhanced by the development on an appropriate laser and tracking system (the Geodynamics Laser Ranging System, or GLRS) to be flown in the first instance aboard the Space Shuttle and then, on an ongoing basis, from one of the polar-orbiting platforms of the Earth Observing System (Eos). This approach would permit deployment of a greatly enlarged array of inexpensive corner reflectors on the ground in association with only one sophisticated satellite instrument, reversing the present approach, which requires a relatively inexpensive satellite but many ground-based instruments. This development fits naturally near the beginning of the progressive evolution of space-qualified laser systems of increasing power and capability for many different observational purposes. Complementary information on the intermittent deformations associated with individual large earthquakes should be obtainable from an accurate determination of the rotation vector of the Earth, a major purpose of the global network of VLBI and satellite laser-ranging stations. When combined with frequent GPS or GLRS observations near major faults, the spectrum of relaxations of the local strain concentration will provide fundamental insights into the rheology of the mantle.

Figure 3.14 THE GLOBAL POSITIONING SYSTEM (GPS). Satellites of the GPS will provide a highly accurate frame of reference on the Earth's surface, with important applications to studies of the lithosphere.



3.B.3. Polar Motion and Earth Rotation

Accurate measurement of polar motion and of the length of day are important to investigations of core-mantle coupling. Highly precise results are necessary to distinguish this effect from many others at work, such as the shifting distributions of atmospheric mass and of ice cover on the Earth's surface. Recent VLBI measurements have established a new standard of accuracy for these investigations (Figure 3.5) and should be encouraged and expanded.

Future studies of polar motion and Earth rotation will be coordinated internationally by the International Earth Rotation Service (IERS), newly established by the IUGG and the International Astronomical Union (IAU). Data from a number of countries that operate laser-ranging or VLBI stations will supplant the optical-astronomy data utilized until now by the International Polar Motion Service, which will be superseded by IERS early in 1988. Results from NASA's Crustal Dynamics Project will furnish the major part of the IERS data for some years to come.

3.B.4. Time-Dependent Magnetic Field

Another objective requiring recurrent global observations is mapping the secular variations of the Earth's magnetic field. These are related to convection patterns in the core of the Earth, and the statistics of their variation provide important checks upon theories of the geomagnetic dynamo. Previous magnetic field observations gathered by the Polar-Orbiting Geophysical Observatory (POGO) satellites from 1965 to 1971 and by Magsat in 1980 have raised important questions about how and why the field varies on multiyear timescales. A first step in the systematic investigation of such questions can be taken through flight of the proposed joint U.S./France Magnetic Field Explorer/Magnolia (MFE/Magnolia) mission, preferably during the declining phase of a solar cycle. This mission will not only provide an important third "snapshot" of the geomagnetic field (following the POGO and Magsat observations) at intervals of about a decade, but will also furnish the first accurate global data set for continuous analysis of the field's secular variation.

International research on secular geomagnetic-field changes is coordinated through the IUGG's International Association of Geomagnetism and Aeronomy (IAGA). Because IAGA does not sponsor specific projects, advanced scientific planning for MFE/Magnolia and related research is being done through the recently created *ad hoc* International Working Group on Magnetic Field Satellites (IWGMFS), which brings together research teams from the United States and other nations, primarily Japan and France.

3.B.5. Land-Surface Data

Another field of fundamental importance to the interpretation of the present structure of the solid Earth is the topography of the land surface. A digitized map of uniform quality and resolution over the globe would be an invaluable resource for studies of gravitational anomalies, geologic structures and lithology, drainage patterns, and the analysis of soils and surface vegetation. In most of the world a vertical precision of 10 m with a horizontal resolution of 500 m would represent a major advance over presently available information, although ultimately a horizontal resolution approaching 25 m (to match that obtained from an imaging spectrometer or synthetic-aperture radar) is needed. It is proposed to obtain this information in the first instance using a scanning radar altimeter in polar orbit, followed in due course by a higher-resolution survey using a Lidar Atmospheric Sounder and Altimeter (LASA) on the Earth Observing System (Eos).

In addition to topography, global observations of lithology and mineral composition are required to delineate surface geologic structures and to identify key areas for more intensive *in situ* study. The Multi-Spectral Scanner and Thematic Mapper aboard the LANDSAT series of satellites, together with similar instruments aboard the SPOT (Système pour l'Observation de la Terre) series, are important tools in use now, and planned developments in infrared spectrometry and synthetic-aperture radar promise major advances in the future.

3.B.6. Gravity Geoid and Crustal Magnetism

The present structural features of the solid Earth can be determined accurately by precision measurements of global fields. Over the past decade, a sequence of satellites carrying altimeters has revealed the major features of the geoid, at least over the ocean, to an accuracy of better than 1 m and has provided a fundamentally new constraint on models of the Earth's interior and on theories of its past development.

The shape of the geoid is the manifestation in the gravitational field of a combination of the topography of the solid surface and of the distribution of rocks of different density below. As the geoid becomes known to greater accuracy and horizontal resolution, it promises to become an ever-more-powerful aid in interpreting subsurface structures. The logical next step in this process is the Geopotential Research Explorer Mission (GREM), which has been specifically designed to achieve this greater accuracy of a few centimeters over the ocean and to yield the first measurements ever on scales of a few hundred kilometers on the continents in areas heretofore inaccessible (see Section 9.D.2 of Chapter 9). In addition, changes with time of the Earth's gravity field (already inferred from the LAGEOS-1 orbit and from the study of ancient land surfaces) measure the post-glacial rebound of the solid Earth, important to determinations of mantle viscosity.

International studies of gravity and the geoid are coordinated through the IUGG's International Association of Geodesy (IAG). In the area of space-mission planning, a current major activity is discussion of possible substantial European participation in GREM within a joint steering committee of NASA and the European Space Agency (ESA). There is also a NASA planning team concerned with later flight of the Gravity Gradiometer Explorer Mission (GGEM), which will represent the culmination of a long-term program of space observations designed for increasingly precise investigations of the Earth's gravitational field.

3.B.7. Global Seismic Properties

A major example of *in situ* studies needed to complement space observations is seismic tomography, now being applied on a global scale. If seismic velocity anomalies are interpreted as arising from mantle convection, they can account for most of the Earth's long-wavelength gravity field. It thus appears that we are beginning to gather our first images of the temperature contrasts associated with this convection. Observations of seismic anisotropy also place fundamental constraints on mantle convection.

The combination of seismic tomography with gravity data provides a unique opportunity for mapping the interior structure of the Earth. However, the discoveries emerging with the use of tomographic methods in seismology are at present severely limited by the availability of suitable global digital seismic data. A new digital seismic network has been proposed and is being funded by NSF with support by USGS. The goal of this new-generation global seismographic network is to produce broadband, wide-dynamic-range digital data from a global network of at least 100 stations and provide for the timely collection and distribution of these data to a wide variety of users. The large quantity of data ($8x10^{12}$ bits/year) and the number of data-collection centers (which could be a dozen or more) place strong emphasis on an efficient system for data collection and management. Proposals have also been developed and submitted to NSF for a system of portable seismic arrays. These arrays, which would include as many as 1,000 instruments, would be used to map regional and local lithospheric structure by seismic reflection profiling.

3.B.8. Research Foci and Process Studies

Research progress toward understanding global change on longer timescales requires not only global observations, but also research foci and process studies designed to address specific topics and mechanisms (Table 3.2). Discussion earlier in the present chapter has underscored the importance of comparative planetology and early-Earth studies, of mantle circulation, and of magmatism and volcanoes for a deeper inderstanding of Earth system evolution on these timescales. Plate tectonics appears to provide the key to such an understanding and has clarified the task of scientists now seeking to unravel the mechanisms of continental assembly and evolution. Motions and deformations of the lithospheric plates have been discussed in sections 3.B.1 and 3.B.2 above, whereas core dynamics and the Earth's dynamo have been considered in sections 3.B.3 and 3.B.4.

The mid-ocean ridges are centers from which oceanic plates are spreading, driven by warm rising currents in the mantle. They are locations of intense volcanic and earthquake activity. They are also sites of hydrothermal circulation, which has significant long-term influence on the geochemistry of sea water and is associated with mineral deposits and specialized ecosystems.

Geologic processes at the land surface, although active throughout the history of the Earth and an integral part of its long-term evolution, also have particular significance for soil formation and development and as indicators of climate in the recent past. An example is provided by the patterns of sand dunes and deposits of wind-blown dust revealed by satellite imagery with appropriate *in situ* validation. For presently active regions, correlations are being established with wind observations and models of particulate transport. This information can then be applied to other areas that are now vegetated to estimate climate variables since the last ice age. Similar inferences need to be encouraged with respect to drainage patterns, lake levels, and soil formation. A study of the processes leading to soil formation and evolution provides an important research focus for this activity.

This discussion illustrates the importance of process case studies and the identification of their signatures in the lithological, fossil, and geomorphological records. For example, the differentiation of minerals within bodies of magma and their migration through (and concentration in) neighboring rock strata are controlled by convection in heterogeneous fluids and the chemistry of aqueous solutions at high pressures and temperatures. The signatures include identification of minerals at outcrops, the clues to subsurface structure provided by surface morphology and vegetation, stratigraphy revealed by seismic surveys, and direct sampling from drill holes. This differentiation also influences types of volcanic eruptive activity, as exemplified in Figure 3.11.

Although much of this activity must take place *in situ*, experience with LANDSAT data has shown that the broad-scale perspective and pattern recognition provided by space and airborne remote sensing is critical to identifying the most significant locations for *in situ* study, and to interpolation between such locations. In the future, the remote identification of groups of minerals and the signatures in vegetation of geological structures by imaging spectrometers, and the detailed surface structure revealed by lidar and synthetic-aperture radars, promise to open up major new capabilities and to increase confidence in extrapolations from local case studies to worldwide areas.