SCIENCE STRATEGY FOR THE EARTH OBSERVING SYSTEM

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1.0. INTRODUCTION

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.

Earth System Science: A Closer View, 1988

1.1. NEED FOR AN EARTH OBSERVING SYSTEM

Since space exploration began in the late 1950s, space technology has been used to investigate the other planets of the solar system, exploiting the opportunity provided by satellites to learn about worlds far distant from our own. Now, that same technology provides the global perspective needed for an integrated, long-term, scientific investigation of our home planet.

Why is this "Earth Observing System" so important? In addition to the broader goal of learning about the Earth as part of the continuing scientific enterprise, this mission is driven by the need to understand human-induced changes on the Earth system. We know from the geologic record that the Earth has undergone significant alterations in its physical configuration since the planet was formed some 4.5 billion years ago. Indeed, the entire history of the Earth is a dynamic continuum, with changes on all time scales. This evolving character of the Earth makes its scientific study both interesting and difficult. What is disturbing, however, is evidence that the rates of change for several key components of the system are increasing dramatically, and that human activity is responsible. Within the span of a single human lifetime, we can detect significant differences in ecology, atmospheric chemistry, terrestrial and oceanic ecosystems, and water quality.

Whether human society affects the Earth system is no longer a question. The questions have now become, "How severe is that effect, and what can be done about it?"

1.2. INEVITABILITY OF GLOBAL CHANGE

Continued change in the Earth system is inevitable. Increases in atmospheric concentrations of carbon dioxide can be tied directly to combustion of fossil fuels, deforestation, and other human-instigated sources. Without scientific evidence documenting the consequences of human action, repercussions such as the doubling of atmospheric carbon dioxide remain the subject of debate. Decisionmakers need scientific guidance to make sound policy choices, thereby altering human behavior and protecting the environment.

Without a firm understanding of how we affect the world, present conduct could go unchecked. The following factors serve as typical agents of human-induced global change:

- Increases in world population, the strong association between standard of living and energy consumption, and economic factors linked with the abundance of fossil fuels suggest that carbon emissions into the atmosphere will increase for the foreseeable future.
- Even if the countries of the world agreed today to freeze emissions of carbon dioxide at current amounts, the atmospheric concentration would continue to increase. Stabilizing atmospheric CO_2 at the current level, which is 25 percent above the pre-industrial concentration, would require an unrealistic 80 percent reduction of carbon emissions.
- Population increases define land use changes and agricultural production in ways that contribute to global change. For example, rice cultivation and cattle production are significant sources of methane and other important radiatively active gases in the atmosphere.
- Chlorofluorocarbons (CFCs) manufactured for refrigeration and air conditioning break down when they reach the stratosphere, and produce the chlorine radical that destroys ozone. The chlorine radical has a 100-year residence time in the upper atmosphere, so we are only beginning to see the ramifications to stratospheric chemistry.

Enhanced quality of life must be tempered with a realization of the consequences imposed upon the environment; unfortunately, future global changes will not be limited to the causal factors scientists have already identified. Subtle, yet significant, changes that are now undetected will also occur. Thus, the inevitability of global change and the prospect of unanticipated modifications of the global environment add urgency to the need to understand the operation of the Earth system.

The societal implications of human-induced global change are enormous. Global climate models predict that a doubling of carbon dioxide concentrations in the atmosphere, as compared to pre-industrial concentrations, will result in a 2 to 4°C globally averaged warming of temperatures in the troposphere. The last global temperature change that large—a decrease instead of an increase—occurred during the Ice Age advance and retreat, and brought glacial ice within the boundaries of what is now the United States. However, the Ice Age advance/retreat took place over tens of thousands of years, whereas present-day temperature fluctuations are projected to occur within a century. Atmospheric CO_2 will rise to concentrations substantially greater than any in the last 160,000 years, as evidenced by measurements in air bubbles trapped in ice cores from Antarctica and Greenland.

Global warming is not the only consequence of changing atmospheric composition. The altered circulation associated with shifts in atmospheric temperature will also affect water balances. Some climate simulations show an increased frequency of drought in many mid-latitude continental regions. Such droughts would reduce water availability and quality for industry, agriculture, and human consumption. Warming may also melt portions of the polar ice sheets and cause the sea level to rise, threatening coastal cities and environments.

If researchers can improve predictions of the plausible consequences of future change, that will provide society the opportunity to adapt to and minimize negative effects. Worldwide recognition of the challenges presented by anthropogenic global change has led to a major international effort known as global change research. The United States participates through the U.S. Global Change Research Program (USGCRP), which coordinates the efforts of numerous Federal agencies under the guidance of the Committee on Earth and Environmental Sciences (CEES).

The National Aeronautics and Space Administration (NASA) leads the U.S. contribution to the international Global Change Research Program (GCRP) via its Mission to Planet Earth (MTPE), with the Earth Observing System (EOS) serving as its centerpiece. This NASA-initiated concept uses space- and ground-based measurement systems to provide the scientific basis needed to address global change issues. Interagency and international collaborations—MTPE Phase I—precede the EOS flight segment, establishing and continuing the baseline data sets needed to document trends. They furnish observations on a global scale that are needed to monitor environmental change, and to initialize and verify models of the Earth system.

The space-based component of the MTPE Program includes EOS, Earth Probes dedicated to observations of specific phenomena, operational and research satellites, and future geostationary platforms. No single orbit permits the gathering of complete information on Earth processes. These platforms will provide a constellation of satellites to monitor the Earth from space. Sustained observations will allow researchers to monitor climate variables over time to determine trends; however, space-based monitoring alone is not sufficient. A comprehensive data and information system, a community of scientists performing research with the data acquired, and extensive ground campaigns are all important components. More than any other factor, the commitment to make Earth science data easily available to the research community proves critical to mission success.

[Insert Figure 1. NASA's Mission to Planet Earth]

1.3. NEED FOR INTEGRATED MEASUREMENTS

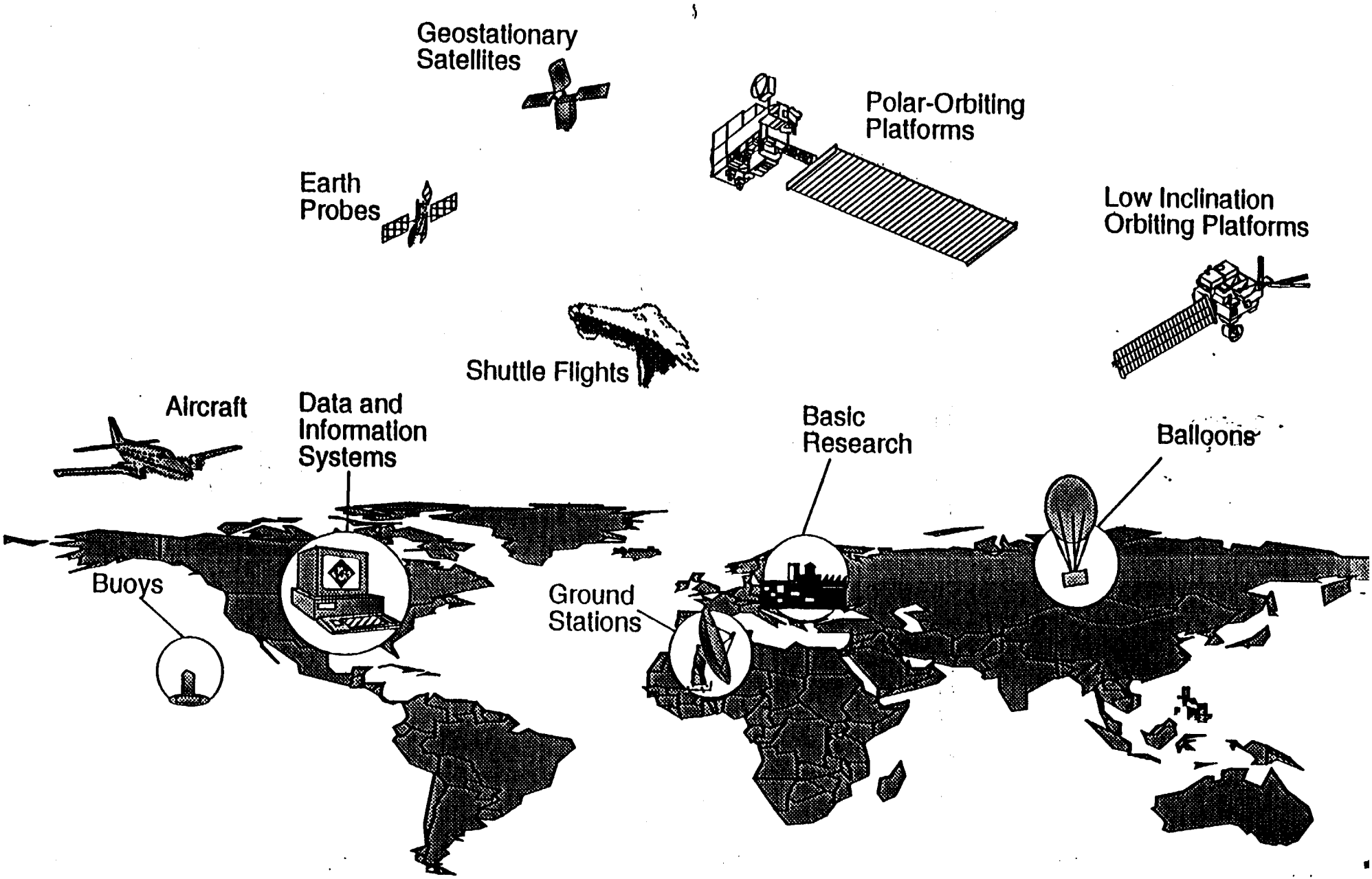

Geostationary Satellites
Polar-Orbiting Platforms
Earth Probes
Low Inclination Orbiting Platforms
Shuttle Flights
Aircraft
Data and Information Systems
Basic Research
Balloons
Buoys
Ground Stations

Figure 1

Predictions of global change show enormous potential for climatic, biological, and hydrological consequences as a result of human activity. Unfortunately, given the critical observational limitations now faced by researchers, even the most comprehensive models produce answers that are hedged with uncertainty. EOS will monitor environmental changes to advance understanding of the entire Earth system, developing a deeper comprehension of the components of that system and the interactions among them. To quantify changes in the Earth system, EOS will provide systematic, continuous observations from low Earth orbit for a minimum of 15 years. By enhancing understanding of the processes involved, EOS will help discriminate anthropogenic and natural changes.

Scientists need long-term, consistent measurements of the key physical variables that define the shifts in state and variability of Earth system components—that is, the atmosphere, hydrosphere, cryosphere, oceans, and land surface. Lacking these measurements, predictions of the complex responses of the Earth system to human activities and natural variations lack an adequate baseline to determine trends. The scientific community agrees that space-based observations hold the key, because satellites provide the only means of capturing a global perspective.

To date, remote sensing of the Earth system largely has consisted of discipline-oriented missions focused on a narrow range of physical phenomena and problems. While the current approach has led to significant gains in understanding the atmosphere, hydrosphere, and biosphere, it does not provide enough information about the coupling of these systems. The fluxes of mass (i.e., water, CO_2, and other trace constituents), heat, and momentum between the land and atmosphere and between the ocean and atmosphere cannot be quantified using data from this discipline-specific approach. Furthermore, current computer simulations include only primitive models of these interactions. These very interactions drive important changes in the Earth system.

To determine the magnitudes and spatial variations of global change, consistent global measurements are needed over a long enough period so that natural variabilities associated with seasons and other cyclical or periodic events can be analyzed. The duration of the observations must be at least 15 years, to span a solar cycle and several El Niño events. These observations must characterize the whole planet and its regional variations, and enable quantification of the processes that govern the Earth system. The full set of required observations requires many instruments on satellites in different orbits. Moreover, certain detailed measurements can only be made *in situ*. To obtain global coverage, satellites must be placed in both polar and inclined orbits—the former because equatorial or near-equatorial orbits do not view

the entire planet, and the latter for sampling the diurnal cycle or for special studies at lower latitudes.

[Insert Figure 2. Orbits Required to Establish a Global Perspective]

Scientists have begun to look at the Earth as a complex, integrated system. This multidisciplinary vision requires comprehensive data collection spanning the geosphere, hydrosphere, atmosphere, cryosphere, and biosphere, and the processes that govern interactions among these subsystems. Indeed, an interdisciplinary approach must be embraced if we are to understand the Earth's systemic behavior.

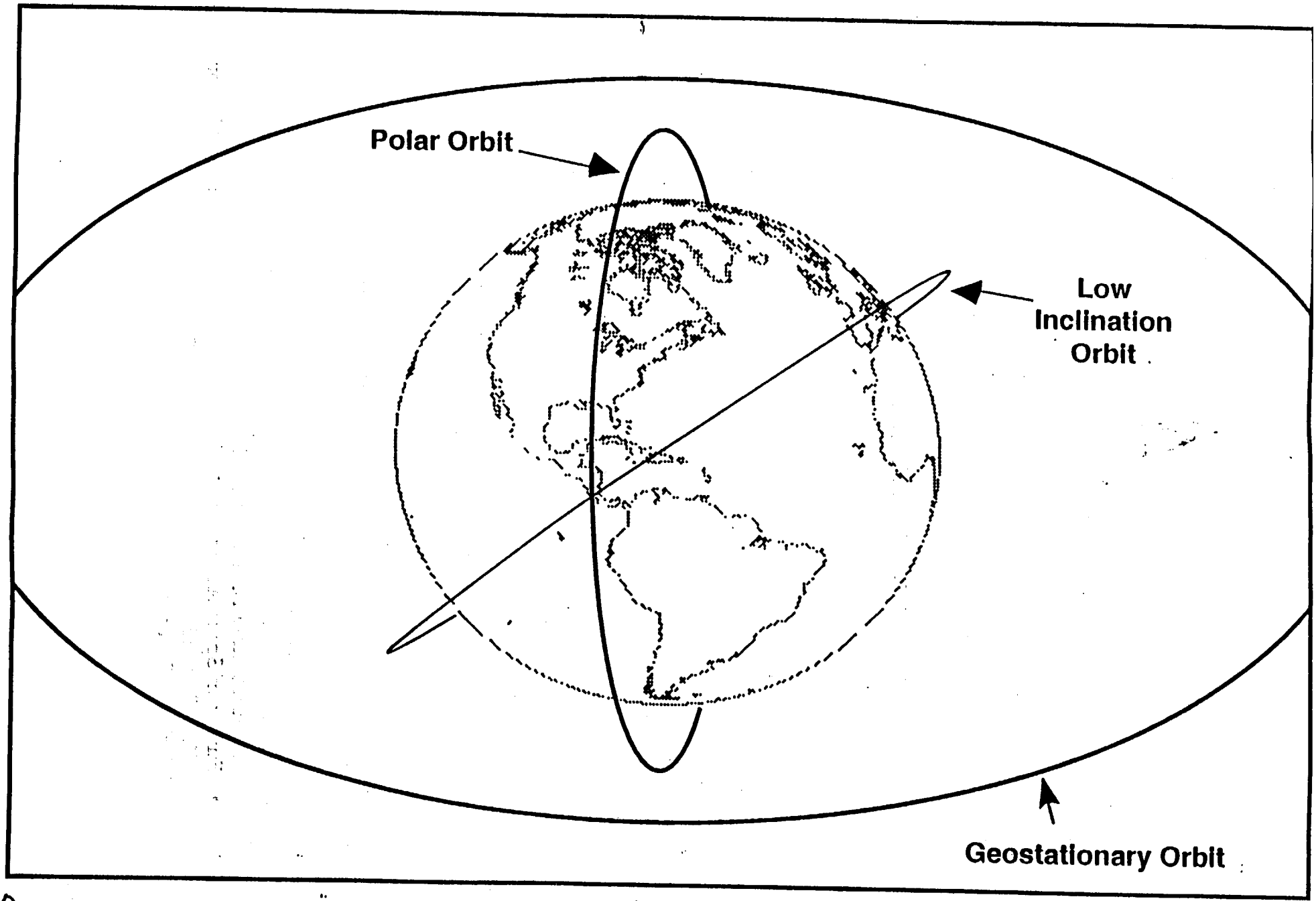
1.4. CHALLENGE FOR EARTH SYSTEM SCIENCE

In addition to integrated measurements of Earth system processes, researchers must also adopt an interdisciplinary approach in analyzing the collected data and disseminating the resulting information. In the past, the diverse disciplines that comprise the Earth sciences developed independently, and scientists and engineers tended to pursue discrete research objectives and strategies. Advances in observational methods, theories, and models in the fields of meteorology, oceanography, bioclimatology, ecology, geochemistry, geomorphology, and hydrology remained unique. Now, however, three forces have combined to alter the modes and focus of research:

1) Discipline studies have matured to the point that investigators are reaching the limits of traditional research, blurring the distinction between disciplines.
2) The perspective of Earth from space encourages an integrated approach, which views the planet as a system.
3) The growing awareness and apprehension about the effects of human-induced global change makes interdisciplinary methods essential.

These three forces have led to the definition of several central problems that require the unified perspective now known as "Earth System Science" (Earth System Science Committee, 1988):

- The greenhouse effect associated with increasing concentrations of carbon dioxide, methane, CFCs, and other radiatively active gases
- Ozone depletion in the stratosphere, resulting in a significant increase in the ultraviolet radiation reaching the Earth's surface
- A diminishing supply of water suitable for human use
- Deforestation and other anthropogenic changes to the Earth's surface, potentially affecting the carbon budget, patterns of evaporation, precipitation, soil erosion, and other components of the system



5p

Fig. 2

- Changes in photosynthesis, respiration, transpiration, and trace gas exchange both on the land and in the ocean
- Decline in the health of vegetation due to long-term changes in the chemistry of the atmosphere, precipitation, runoff, and groundwater.

For those who make observations of the Earth system and develop models of its operation, Earth system science means the creation of interdisciplinary models that couple elements from such formerly disparate sciences as ecology and meteorology. This approach mandates a remote-sensing strategy to ensure collection of the data sought by the scientific community.

EOS satisfies the dual requirements of an integrated approach to Earth observation and the development of meaningful products to aid global change researchers in their investigations. The EOS Program will address high-priority science and environmental policy issues in Earth system science by flying instruments on intermediate-sized and smaller spacecraft. The program also includes a data and information system (i.e., EOSDIS) that will allow Earth scientists to study processes and develop better models.

Experience has demonstrated the need for a functional data system to collect, process, manage, and distribute Earth science data, particularly satellite remote-sensing data. This comprehensive information system proves critical to mission success, considering the wealth of data that will be generated by the EOS satellite series, the missions of our international partners, and ground campaigns—all of which need to be processed, archived, and made readily available. With inputs from the user community, EOSDIS will evolve through several versions. User needs for EOSDIS will become more clearly understood as researchers work with and respond to early versions of the system. User needs will change over time; to succeed, EOSDIS must be responsive to change. Its design and the implementation process must facilitate upgrades, while supporting ongoing operations and user services.

As alluded to above, EOS is part of a larger international partnership, referred to as the International Earth Observing System (IEOS). New data will be provided by a suite of U.S.-provided and international missions:

- NASA EOS missions
- Japan's Advanced Earth Observing System (ADEOS) missions
- NASA and the National Space Development Agency (NASDA) Tropical Rainfall Measuring Mission (TRMM) and follow-ons
- European Space Agency (ESA) Polar-Orbit Earth Observation Mission (POEM) satellites
- National Oceanic and Atmospheric Administration (NOAA) Polar-Orbiting Operational Environmental Satellite (POES) series.

Chapter 3 provides detail about the platforms and payloads to be provided by the IEOS partners; Chapter 2 gives information about the instrument complements that make up the EOS satellite series. Refer to the "1993 EOS Reference Handbook" for indepth coverage of the EOS Program elements (Asrar and Dokken, 1993).

Other satellites not considered part of IEOS provide valuable Earth science data. Though not all-inclusive, the following list represents present-day inputs into the data and information systems of the responsible countries:

- European Remote-Sensing Satellite-1 (ERS-1), which was launched in the summer of 1991
- Upper Atmospheric Research Satellite (UARS), which was launched in the fall of 1991
- Japan's Earth Resources Satellite-1 (JERS-1), which was launched in the winter of 1992
- Ocean Topography Experiment (TOPEX)/Poseidon, which was launched in the summer of 1992
- Sea-Viewing Wide Field Sensor (SeaWiFS), to be launched in 1994.

By 1998, EOSDIS will be fully operational, linking the data holdings of the partner nations and agencies. Assets will be physically distributed, but the system will appear completely integrated to users and will provide researchers with the complete set of capabilities needed for global change science and mission operations. In addition, archived data sets are being transferred to more stable media and are being reprocessed in standard formats to ensure compatibility with future observations. By enhancing the utility of present holdings, the EOSDIS Program assists global change researchers now, rather than waiting for the launch of the first EOS platform.

By the end of this century, a powerful observing system will be in orbit. This system will provide remarkably broad coverage of the Earth in a wide variety of spectral bands, both optical and microwave, with active and passive techniques being used in an unprecedented effort to understand the whole Earth system.

1.5. THE EARTH SYSTEM: TWO WATER-COUPLED SUBSYSTEMS

To understand the strategy that underlies desired observations, it is important to grasp the essential features of the Earth system that are being studied. The Earth system is complex, and important manifestations of global change occur in all its components over a range of spatial and temporal scales. Earth is unique among the planets in its abundance of water in all three phases, which is a consequence of the Earth's radiative balance. In turn, this balance is strongly affected by global biogeochemistry.

Incompatible gases such as oxygen and methane coexist in the Earth's atmosphere, and the resulting disequilibrium for periods longer than the residence time of the gases means that atmospheric composition and climate are intimately tied to biological processes. Moreover, as water transitions through its gaseous, liquid, and solid phases, it acts as a carrier for chemicals and nutrients. As such, understanding even the simplest aspects of the Earth system requires knowledge of geophysics, geochemistry, and biology.

The Earth system can be regarded as two subsystems—physical climate and biogeochemical cycles—linked by the global hydrologic cycle (see Figure 3). An examination of these subsystems and the linkages between them helps to define the critical questions that are being addressed by EOS.

[Insert Figure 3. The Earth System—Two Subsystems Connected by the Hydrologic Cycle]

1.5.1. Physical Climate Subsystem

The physical climate subsystem is sensitive to modifications in the radiation balance of the Earth. These modifications can be caused by increasing atmospheric concentrations of radiation-absorbing gases (Ramanathan et al., 1989). Moreover, it now is apparent that the perturbations to the planet's radiative heating mechanism caused by human activities have begun to rival or exceed naturally induced changes.

According to the Intergovernmental Panel on Climate Change (IPCC), increases in radiatively active greenhouse gases (primarily CO_2, CH_4, and CFCs) between 1765 and 1990 have caused a radiative forcing of 2.5 W m^{-2} (IPCC, 1993). This increased trapping of infrared radiation by the Earth's atmosphere represents only about 1 percent of the globally averaged emission of infrared radiation by the Earth system. While this appears to be a small amount, IPCC says that if there is no policy response to this trend, emissions of greenhouse gases will cause a rate of increase of global mean temperature during the next century of about 0.2 to 0.5°C per decade. This range in the estimate of global warming rates reveals the uncertainty surrounding global climate models, caused primarily by knowledge gaps in quantifying cloud generation and radiative processes.

Not all expected warming will be realized immediately, because of the enormous heat-absorbing capacity of the oceans. Turbulent mixing of the added heat within the top 50 to 200 m of the ocean, and large-scale lateral and vertical mixing by circulation in the deeper layers, may delay some of the warming for more than a century. Much more needs to be known, however, about the precise effects of oceanic heat absorption.

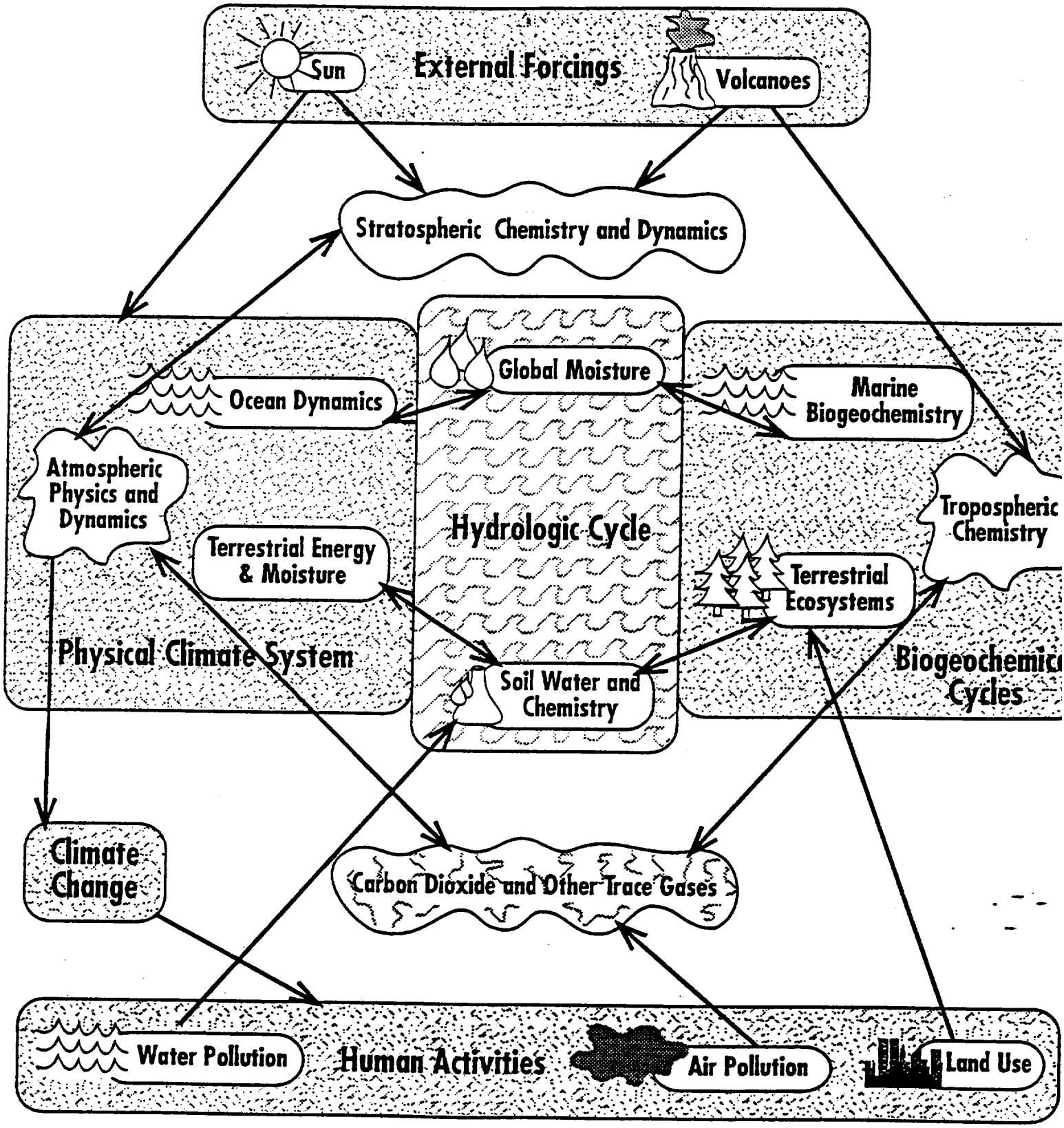

Sun
External Forcings
Volcanoes
Stratospheric Chemistry and Dynamics
Global Moisture
Ocean Dynamics
Marine Biogeochemistry
Atmospheric Physics and Dynamics
Hydrologic Cycle
Tropospheric Chemistry
Terrestrial Energy & Moisture
Terrestrial Ecosystems
Physical Climate System
Soil Water and Chemistry
Biogeochemic Cycles
Climate Change
Carbon Dioxide and Other Trace Gases
Water Pollution
Human Activities
Air Pollution
Land Use

Figure 3

The need for accurate observation, modeling, and prediction of the effects of anthropogenic changes in the Earth's climate subsystem leads to the following specific questions that need to be answered if we are to prepare for future conditions:

- How might the roles of clouds and aerosols in the Earth's radiation and heat budgets change with increased atmospheric CO_2 concentration? What are other radiative feedback mechanisms, and how do they lead or respond to changes in climate?
- How do the oceans interact with the atmosphere in the transport and uptake of heat, and what role do they play in global and regional climatic variability?
- How do atmospheric and oceanic circulations affect the mass balance of ice sheets, glaciers, and ice caps, and what is the effect on sea level?

Answering these questions alone is a challenge, but they are only the beginning of the list, which lengthens with a cursory examination of the other major subsystem.

1.5.2. Biogeochemical Cycles

In the past 100 years or so, fundamental elements of the biogeochemical cycles of the Earth have been substantially altered; however, the physical manifestation of these changes is not known. For example, since 1850, atmospheric carbon dioxide has increased by 25 percent and atmospheric methane by more than 100 percent (Dickinson and Cicerone, 1986). It also appears that the capacity of the troposphere to oxidize trace constituents has decreased during the same period.

In addition, ozone concentrations in the stratosphere have decreased, most notably above Antarctica and the Antarctic Ocean, and potentially in the mid-latitudes of the northern hemisphere, while tropospheric ozone concentrations have increased in both rural and urban areas worldwide.

Cycles of essential elements within ecosystems have been greatly affected by changes in land use and management and by the changing atmosphere. The same shifts have taken place in the interactions between terrestrial ecosystems, the atmosphere, and the hydrosphere. Precipitation chemistry has also changed over widespread areas, and the composition of surface water and groundwater continues to be altered, in response to land use and industrial development practices.

Global change researchers must address the following specific questions about the Earth's biogeochemistry to shed light on the above processes:

- What roles do the oceanic and terrestrial biospheres play in the changing global carbon budget? How are these roles shifting as a result of increasing atmospheric CO_2?
- How are changes in the physical/chemical climate system linked to changes in the processes of photosynthesis and evaporation? What are the principal anthropogenic sources of carbon dioxide and methane, and what are the contributions from fossil fuels, biomass burning, and changes in land use versus natural sources?
- Are the atmospheric lifetimes of key radiatively and chemically active gases being altered as a result of changing chemical composition of the troposphere? What determines the oxidizing capacity of the troposphere, and how are biological and industrial processes affecting it?
- What are the likely effects on natural and managed ecosystems of increased carbon dioxide, acid deposition, shifting rainfall patterns, and ozone depletion?
- What are the feedback mechanisms and linkages between climate, atmospheric fluxes to the ocean, and primary production in the ocean?
- What are the magnitudes, locations, and frequencies of volcanic eruptions, and what are their effects on climate? How do changing patterns of climate and land use affect the flux of aerosols into the atmosphere?

1.5.3. Hydrologic Cycle

The physical climate and biogeochemical cycles subsystems are linked by the hydrologic cycle, which functions across a wide spectrum of temporal and spatial scales. The hydrologic cycle affects the global circulation of the atmosphere and ocean; phase changes of water on Earth involve storage and release of latent heat, which drives atmospheric circulation and globally redistributes both water and heat. Water's efficiency as a solvent also allows for low-temperature biogeochemical processes. Thus, the hydrologic cycle is the integrating process for the fluxes of water, energy, and chemical elements among components of the Earth system (Committee on Opportunities in the Hydrologic Sciences, 1991).

Researchers are striving to delve into water's role in regulating physical, chemical, and biological processes in circumstances where human activity has become indistinguishable from natural events. To understand how global change may influence global water balances, we must know more about spatial and temporal variations in the storage of water in its various reservoirs and the magnitude of transfers between these reservoirs. In addition, the regulation of these water transfers by physical and biological processes and their influence on climate needs more detailed investigation.

Specific questions about the hydrologic cycle to be asked by the Earth science community include the following:

- How will atmospheric variability and climate change affect patterns of water vapor, precipitation, evapotranspiration, and soil moisture—as well as distributions of liquid water, snow, and ice—on the Earth's surface? How will these changes influence the atmosphere?
- What are the mechanisms for the transfer of water among the hydrologic reservoirs, and what are the associated directions and magnitudes of transfer? How will the global distribution and fluxes of water change as a result of human activities and climatic variability?
- How does soil moisture vary in time and space, and what are the mechanisms controlling rainfall in arid and semi-arid regions? How does this variability affect the hydrology, geomorphology, and ecology of such regions, and how do these variations translate into regional fields of carbon exchange?
- How does climatic change affect the cryosphere?

These questions, and many more, must be answered before we can hope to predict and adjust to future global changes in the Earth system. EOS has been designed specifically to provide the opportunity for scientists and policymakers to address these questions. Chapters 4 through 10 focus on the specific answers to be sought via EOS observations.

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2.0. AN OVERVIEW OF EOS

There is concern that human activities may be inadvertently changing the climate of the globe through the enhanced greenhouse effect....

Scientific Assessment of Climate Change, Intergovernmental Panel on Climate Change, 1990

2.1. SCIENCE PRIORITIES FOR EOS

The purpose of the Earth Observing System is to determine the extent, causes, and regional consequences of global climate change. The extent—the change in average temperature and the time scale over which it will occur—is presently unknown. The causes can be either natural or human-induced; to separate the natural from anthropogenic effects, we must understand and model the natural events and processes. Regional and global consequences (i.e., changes is precipitation patterns, length of growing season, severity of storms, sea level, etc.) must be understood if we are to determine those aspects of climate change that prove most detrimental and those requiring adaptation if we cannot avoid them.

The behavior and evolution of the climate system is determined by complex processes within and interactions among the Earth system components—atmosphere, oceans, biosphere, water, and snow and ice. There are many important questions to be asked about global change, but financial constraints prevent any research program from addressing them all. With this in mind, the EOS Program has been designed through priorities established by research and policymaking bodies, and the investigators who will be analyzing the remotely sensed observations.

The objectives of USGCRP were articulated by CEES in a document that accompanied the President's FY91 budget submission (CEES, 1990), describing the broad priorities that should be pursued in order to yield the most relevant knowledge about global change (see Figure 4). The development of this science strategy involved a mandate to support the overall objectives of the broad U.S. and international global change scientific effort, keeping in mind financial limitations while still encouraging full participation by the entire Earth science community. As Figure 4 illustrates, emphasis has been placed on global climate change, stressing interactions between disciplines. Interdisciplinary science and process studies provide the best opportunity to understand and discriminate between natural and human-induced changes. Ultimately, knowledge gleaned from the seven prioritized categories will yield integrated conceptual and predictive models, and provide policymakers the guidance needed to make sound environmental policy decisions.

[Insert Figure 4. USGCRP Science Priorities]

The goals established by CEES remain central to the work of EOS; however, policy questions and funding restrictions dictate that these broad areas of research be more explicitly ranked. IPCC—a joint effort of the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP)—has been a leader in shaping scientific knowledge of the Earth system into information useful for policymakers. As such, IPCC has targeted several key "scientific uncertainties" that must be addressed in order to understand how human activities change climate:

- **Clouds**—Primarily cloud formation, dissipation, and radiative properties, which influence the response of the atmosphere to greenhouse forcing
- **Oceans**—The exchange of energy between the ocean and the atmosphere, between the upper layers of the ocean and the deep ocean, and transport within the ocean, all of which control the rate of global climate change and the patterns of regional change
- **Greenhouse Gases**—Quantification of the uptake and release of greenhouse gases, their chemical reactions in the atmosphere, and how these may be influenced by climate change
- **Polar Ice Sheets**—Predictions of future sea levels and sea state.

IPCC added that studies of land surface hydrology and of impact on ecosystems are also important (Houghton et al., 1990).

The uncertainties cited by IPCC, supplemented by studies by other agencies such as the Environmental Protection Agency (EPA) and by the EOS investigators themselves, have been embodied in a set of seven priorities that have now been accepted by much of the Earth science community as the most important goals for EOS (Moore et al., 1991). If we are to understand climate and how the human species modifies it, we must develop a quantitative understanding of the following key issues:

1) **Clouds, Radiation, Water Vapor, and Precipitation**
   - Cloud formation, dissipation, and radiative properties, which influence the response of the atmosphere to greenhouse forcing
   - Large-scale hydrology and moisture processes, including precipitation and evaporation
2) **Productivity and Circulation of the Oceans, and Air-Sea Exchange**
   - Exchange of energy, water, and chemicals between the ocean and atmosphere and between upper layers of the ocean and deep ocean
3) **Sources and Sinks of Greenhouse Gases and their Atmospheric Transformations**

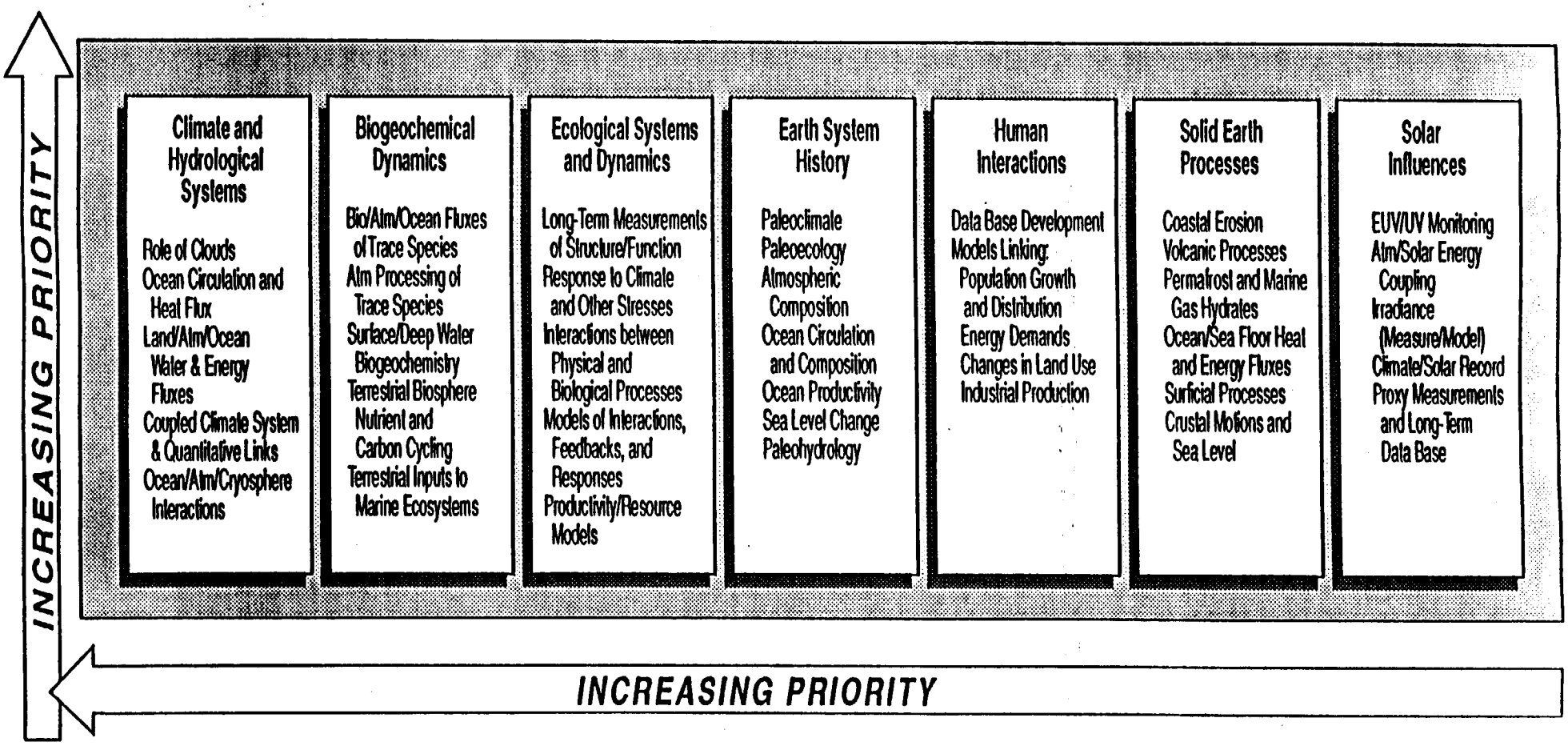
INCREASING PRIORITY
Climate and Hydrological Systems
Role of Clouds
Ocean Circulation and Heat Flux
Land/Atm/Ocean Water & Energy Fluxes
Coupled Climate System & Quantitative Links
Ocean/Atm/Cryosphere Interactions
Biogeochemical Dynamics
Bio/Atm/Ocean Fluxes of Trace Species
Atm Processing of Trace Species
Surface/Deep Water Biogeochemistry
Terrestrial Biosphere Nutrient and Carbon Cycling
Terrestrial Inputs to Marine Ecosystems
Ecological Systems and Dynamics
Long-Term Measurements of Structure/Function
Response to Climate and Other Stresses
Interactions between Physical and Biological Processes
Models of Interactions, Feedbacks, and Responses
Productivity/Resource Models
Earth System History
Paleoclimate
Paleoecology
Atmospheric Composition
Ocean Circulation and Composition
Ocean Productivity
Sea Level Change
Paleohydrology
Human Interactions
Data Base Development
Models Linking:
Population Growth and Distribution
Energy Demands
Changes in Land Use
Industrial Production
Solid Earth Processes
Coastal Erosion
Volcanic Processes
Permafrost and Marine Gas Hydrates
Ocean/Sea Floor Heat and Energy Fluxes
Surficial Processes
Crustal Motions and Sea Level
Solar Influences
EUV/UV Monitoring
Atm/Solar Energy Coupling
Irradiance (Measure/Model)
Climate/Solar Record
Proxy Measurements and Long-Term Data Base
INCREASING PRIORITY

Figure 4

- Links to the hydrologic cycle and ecosystems, transformations of greenhouse gases in the atmosphere, and interactions with climatic change

4) **Changes in Land Use, Land Cover, Primary Productivity, and the Hydrologic Cycle**
   - Improved estimates of runoff over the land surface and into oceans
   - Sources and sinks of greenhouse gases
   - Exchange of moisture and energy between the land surface and atmosphere
   - Changes in land cover
5) **Glaciers and Polar Ice Sheets, and Sea Level**
   - Predictions of sea level and global water balance
6) **Coupling of Ozone Chemistry with Climate and the Biosphere**
   - Chemical reactions, solar-atmosphere relations, and sources and sinks of radiatively important gases
7) **Role of Volcanoes in Climate Change**
   - Volcanoes as sources of atmospheric aerosols and gases
   - Role of volcanoes in the sulfur cycle.

2.2. COMPONENTS OF EOS

EOS supports these seven priorities for Earth system science through four distinct mission objectives:

1) Create an integrated scientific research program that will support the study of the Earth's climate system, hydrologic cycle, and biogeochemical cycles
2) Acquire and assemble, over a 15-year period, a global database of established quality and reliability, mainly from remote-sensing measurements
3) Develop a comprehensive data and information system to serve the needs of scientists from a variety of disciplines studying planet Earth
4) Improve predictive models of the Earth system, focusing on interaction of system components such as air-sea coupling or biological effects on climate.

The EOS mission combines observations and interpretation of data with a scientific research effort. The approach can best be characterized as creating an information system that provides the geophysical, chemical, and biological information necessary for an intense study of planet Earth. In combination with the MTPE Phase I missions, the highly focused Earth Probes satellites, future geostationary platforms, and supporting ground campaigns planned by the U.S. and its international partners, EOS will provide a vast library of data and products for access by the user community (see Figure 5). EOSDIS will encourage interdisciplinary research and assist in breaking down the

intellectual barriers between the traditional disciplines of Earth science by offering an integrated view of environmental data.

[Insert Figure 5. EOS and Earth System Modeling]

2.2.1. EOS Instruments

To provide continuous observations of global climate change, flights of the principal EOS spacecraft will be repeated on 5-year centers to ensure adequate coverage for at least 15 years (see Table 1). The names of the spacecraft series initial launch date, launch vehicle class, and disciplinary focus follow:

- EOS-AM (June 1998, IELV)—Characterization of the terrestrial and oceanic surfaces; clouds, radiation, and aerosols; Earth's radiative balance; and the role of volcanoes in climate
- EOS-COLOR (1998, SELV)—Ocean color and productivity
- EOS-AERO (2000, SELV)—Atmospheric aerosols and ozone
- EOS-PM (2000, IELV)—Clouds, precipitation, and radiative balance; terrestrial snow and sea ice; sea-surface temperature; terrestrial and oceanic productivity; and atmospheric humidity and temperature
- EOS-ALT (2002, MELV)—Ocean circulation, ice sheet mass balance, land-surface topography, and cloud height
- EOS-CHEM (2002, IELV)—Atmospheric chemical species and their transformations.

[Insert Table 1. EOS Satellites and Payload Configurations]

Payloads of the follow-on EOS spacecraft could change, depending on the evolution of scientific understanding and the development of technology.

The EOS Program includes nine intermediate-sized spacecraft—three of which will be morning sun-synchronous (EOS-AM series), three afternoon sun-synchronous (EOS-PM series), and three sun-synchronous polar (EOS-CHEM series). The three smaller spacecraft that comprise the EOS-ALT series will be placed into a sun-synchronous polar orbit, and five very small spacecraft will have a 57° inclined orbit (EOS-AERO series). A one-time data purchase mission (EOS-COLOR) will be placed into a near-polar, sun-synchronous, descending orbit by a small expendable launch vehicle.

The EOS instruments will provide essential observations of the interactions between Earth system components. The EOS science program will combine the measurements from the assembled suite of instruments, using some instruments to correct the measurements of others or to provide data products from more than one instrument. This strategy permits the extraction of parameters that cannot be reliably measured with observations

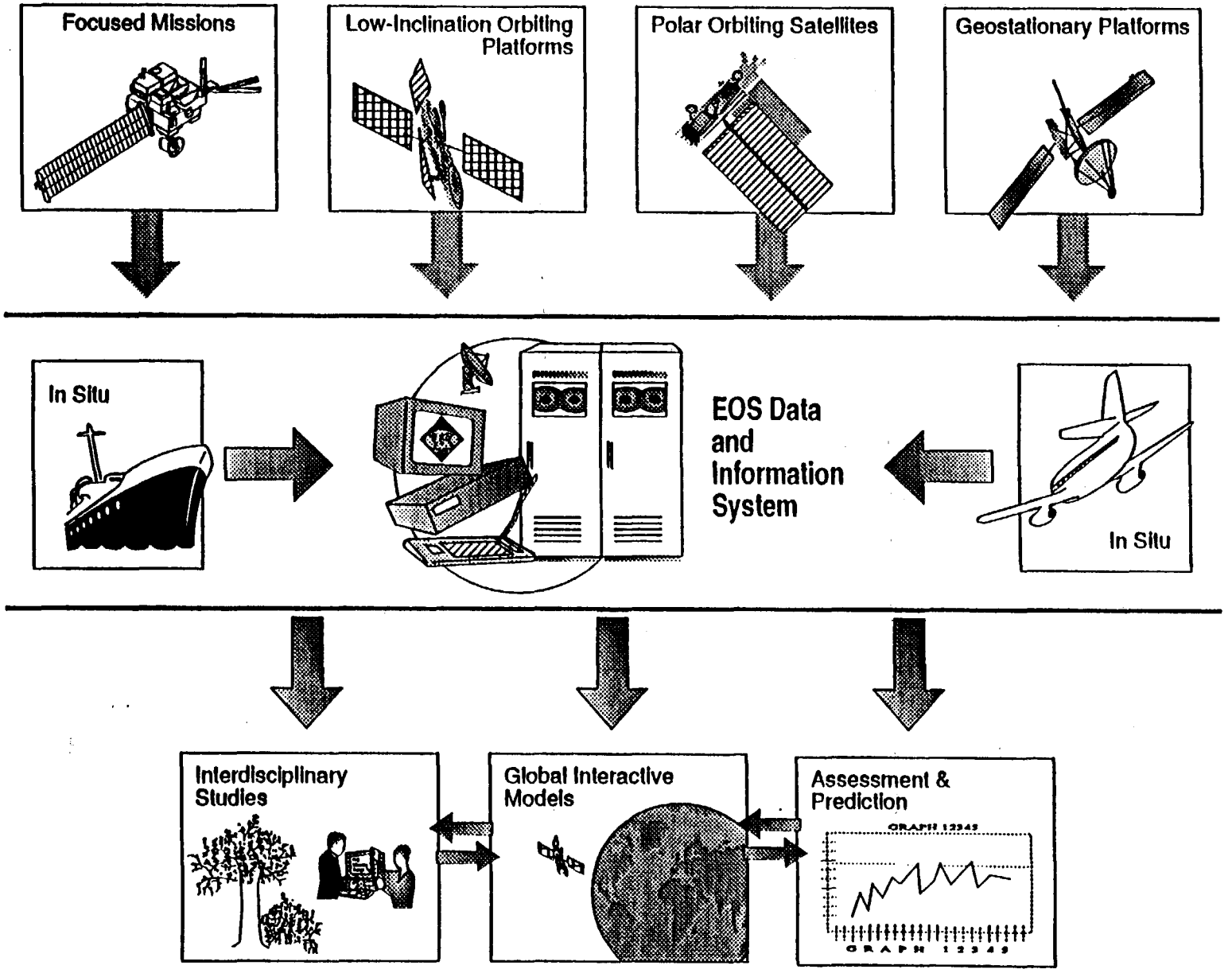
Focused Missions
Low-Inclination Orbiting Platforms
Polar Orbiting Satellites
Geostationary Platforms
In Situ
EOS Data and Information System
In Situ
Interdisciplinary Studies
Global Interactive Models
Assessment & Prediction

Figure 5

Launch	Spacecraft	Lifetime	Instrument Complement					
1998	AM1	5	MODIS	MISR	CERES (2)	MOPITT	ASTER	
2003	AM2	5	MODIS	MISR	CERES	EOSP	TES	MOPITT*
2008	AM3	5	MODIS	MISR	CERES	EOSP	TES	
1998	COLOR	3	SeaWiFS-Type					
2000	AERO1	3	SAGE III					
2003	AERO2	3	SAGE III					
2006	AERO3	3	SAGE III					
2009	AERO4	3	SAGE III					
2012	AERO5	3	SAGE III					
2000	PM1	5	MODIS	AMSU	MIMR	AIRS	MHS	CERES (2)
2005	PM2	5	MODIS	AMSU	MIMR	AIRS	MHS	CERES
2010	PM3	5	MODIS	AMSU	MIMR	AIRS	MHS	CERES
2002	ALT1	5	GLAS	TMR	SSALT	DORIS		
2007	ALT2	5	GLAS	TMR	SSALT	DORIS		
2012	ALT3	5	GLAS	TMR	SSALT	DORIS		
2002	CHEM1	5	HIRDLS	SOLSTICE II	ACRIM	MLS	SAGE III	TBD(J)
2007	CHEM2	5	HIRDLS	SOLSTICE II	ACRIM	MLS	SAGE III	TBD(J)
2012	CHEM3	5	HIRDLS	SOLSTICE II	ACRIM	MLS	SAGE III	TBD(J)

*Accommodation of MOPITT on EOS-AM2 to be confirmed

Table 1

from a single instrument. Observations from the EOS platforms will be fed into global and regional data assimilation models that function as part of EOSDIS, with these models helping to provide continuous calculations of the principal fluxes between components.

Each instrument Team Leader or Principal Investigator is supported by a team of scientists and engineers to help build the instrument and to provide the expertise for processing the acquired data to retrieve geophysical and biological information from the signal. The instruments chosen as part of the EOS Program will address the key scientific issues identified above, as highlighted in Table 2. To ensure that the desired measurement objectives are met, the instrument teams work closely with the Interdisciplinary Science Investigation teams (see Section 2.2.3).

[Insert Table 2. EOS Links to Areas of Scientific Uncertainty]

Brief descriptions of the EOS instruments are offered below; for more information, refer to the "1993 EOS Reference Handbook" (Asrar and Dokken, 1993):

- **Instruments in Early EOS Period (1997-2000)**
  - Atmospheric Infrared Sounder/Advanced Microwave Sounding Unit/Microwave Humidity Sounder (AIRS/AMSU/MHS)—Synergistic package that provides temperature and humidity sounding with much better accuracy than current sensors, with temperatures measured to 1K accuracy at 1-km vertical resolution. Team Leader: Moustafa Chahine/NASA Jet Propulsion Laboratory.
  - Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)—Yields high-resolution images of land surface, water, and clouds from visible through thermal infrared wavelengths; one stereophotogrammetric band to enable production of digital elevation models. Team Leaders: Hiroji Tsu/Geological Survey of Japan and Anne Kahle/NASA Jet Propulsion Laboratory.
  - Clouds and Earth's Radiant Energy System (CERES)—Flies on multiple satellites in morning, afternoon, and inclined orbits to measure Earth's radiation balance. Principal Investigator: Bruce Barkstrom/NASA Langley Research Center.
  - EOS Ocean Color Instrument (EOS-COLOR)—Observes ocean color and productivity to provide continuity of SeaWiFS measurements; data purchase mission involving a single launch. Principal Investigator: To be chosen by NASA.
  - Lightning Imaging Sensor (LIS)—Flies in an inclined orbit on TRMM in 1997, providing global observations of lightning distribution and its variability. Principal Investigator: Hugh Christian/NASA Marshall Space Flight Center.

Science Category	EOS Instrument Complement
Sources and sinks of greenhouse gases, which affect predictions of their future concentrations	AIRS/AMSU/MHS, ASTER, HIRDLS, MIMR, MLS, MODIS, MOPITT, NSCAT II, SAGE III, SOLSTICE II, and TES
Clouds and radiative balance, which strongly influence the magnitude of climate change at global and regional scales	ACRIM, AIRS/AMSU/MHS, CERES, EOSP, MIMR, MISR, MODIS, and SOLSTICE II
Oceans, which influence the timing and patterns of climate change	CERES, MIMR, MISR, MODIS, NSCAT II, SSALT, TMR, and EOS-COLOR
Land surface hydrology, which affects regional climate change and water availability	AIRS/AMSU/MHS, ASTER, MIMR, MISR, and MODIS
Polar ice sheets, which affect predictions of global sea level changes	DORIS, GLAS, MIMR, and SSALT
Ecological dynamics, which are affected by and respond to climate change	AIRS/AMSU/MHS, ASTER, MISR, MODIS, and EOS-COLOR

Table 2

- Multifrequency Imaging Microwave Radiometer (MIMR)—Measures precipitation, cloud water, sea surface temperature and roughness, snow and ice extent, snow water equivalence, and soil moisture. Team Leaders: Roy Spencer/NASA Marshall Space Flight Center and an international counterpart to be chosen by ESA.
- Multi-Angle Imaging SpectroRadiometer (MISR)—Globally maps the planetary surface and surface albedo, aerosols, and vegetative properties; provides low-resolution stereophotogrammetric data. Principal Investigator: David Diner/NASA Jet Propulsion Laboratory.
- Moderate-Resolution Imaging Spectroradiometer (MODIS)—Flies in both morning and afternoon orbits to discern comprehensive global geophysical and biological processes for the land, ocean, and atmosphere. Team Leader: Vincent Salomonson/NASA Goddard Space Flight Center.
- Measurements of Pollution in the Troposphere (MOPITT)—Measures carbon monoxide and methane. Principal Investigator: James Drummond/University of Toronto, Canada.
- NASA Scatterometer II (NSCAT II)—Slated to fly on ADEOS IIa in 1999, as reciprocation for the as yet to be named Japanese instrument on the EOS-CHEM series, generates global profiles of wind speed and direction and sea surface stress. Principal Investigator: Michael Freilich/Oregon State University.
- Stratospheric Aerosol and Gas Experiment III (SAGE III)—Generates global profiles of aerosols, clouds, temperature, and pressure in the stratosphere. Principal Investigator: M. Patrick McCormick/NASA Langley Research Center.

- **EOS Instruments Beyond 2000**
  - Active Cavity Radiometer Irradiance Monitor (ACRIM)—Measures exoatmospheric solar irradiance. Principal Investigator: Richard Willson/NASA Jet Propulsion Laboratory.
  - Doppler Orbitography and Radiopositioning Integrated by Satellite/Solid-State Altimeter/TOPEX Microwave Radiometer (DORIS/SSALT/TMR)—Synergistic package that provides precision orbit determination, ocean wave height and wind speed, ocean surface current velocity and sea surface topography, and atmospheric water vapor profiles. Team Leader: To be determined by NASA.
  - Earth Observing Scanning Polarimeter (EOSP)—Globally maps radiance and linear polarization of reflected sunlight to infer aerosol characteristics. Principal Investigator: Larry Travis/NASA Goddard Institute for Space Studies.
  - Geoscience Laser Altimeter System (GLAS)—Measures the topography of glaciers and ice sheets, cloud heights, and droplet sizes. Team Leader: Bob Schutz/University of Texas–Austin.

- High-Resolution Dynamics Limb Sounder (HIRDLS)—Globally measures temperatures, water vapor, and chemical species in the upper troposphere and stratosphere. Principal Investigators: John Barnett/Oxford University and John Gille/National Center for Atmospheric Research.
- Microwave Limb Sounder (MLS)—Observes atmospheric gases important in ozone destruction, especially chlorine and nitrogen species. Principal Investigator: Joe Waters/NASA Jet Propulsion Laboratory.
- Solar Stellar Irradiance Comparison Experiment II (SOLSTICE II)—Measures ultraviolet solar irradiance. Principal Investigator: Gary Rottman/National Center for Atmospheric Research.
- Tropospheric Emission Spectrometer (TES)—Provides global, three-dimensional profiles of virtually all infrared-active gases from the surface to the lower stratosphere. Principal Investigator: Reinhard Beer/NASA Jet Propulsion Laboratory.

2.2.2. EOS Data and Information System (EOSDIS)

EOSDIS provides the infrastructure to facilitate interdisciplinary research about the Earth system. EOSDIS will provide geophysical and biological information, not simply radiance measurements from the instruments. As such, EOSDIS surpasses the role of a mere data archive; rather, it must be considered a valuable interactive resource of data and derived products readily available to the Earth science community. The data system will operate with an unrestricted data policy, so that data for research purposes can be secured by anyone at a reasonable cost.

NASA is implementing EOSDIS using a distributed, open system architecture. This allows EOS elements to reside at various locations to take best advantage of different institutional capabilities and science expertise (see Figure 6). Acting in concert, Distributed Active Archive Centers (DAACs) will support global change researchers whose needs cross traditional discipline boundaries, while continuing to support the particular needs of the discipline community. Eight DAACs covering various types of Earth science data have been selected by NASA to carry out the responsibilities for processing, archiving, and distributing EOS and related data, and for providing a full range of user support. An additional center receives funding through NASA to act as a link between the EOS Program and the socio-economic/educational user community.

[Insert Figure 6. Geographic Distribution of EOSDIS-Sponsored Data Centers]

EOSDIS is the first element of the EOS Program that will be available to the scientific community, offering useful tools at several stages of its evolution.

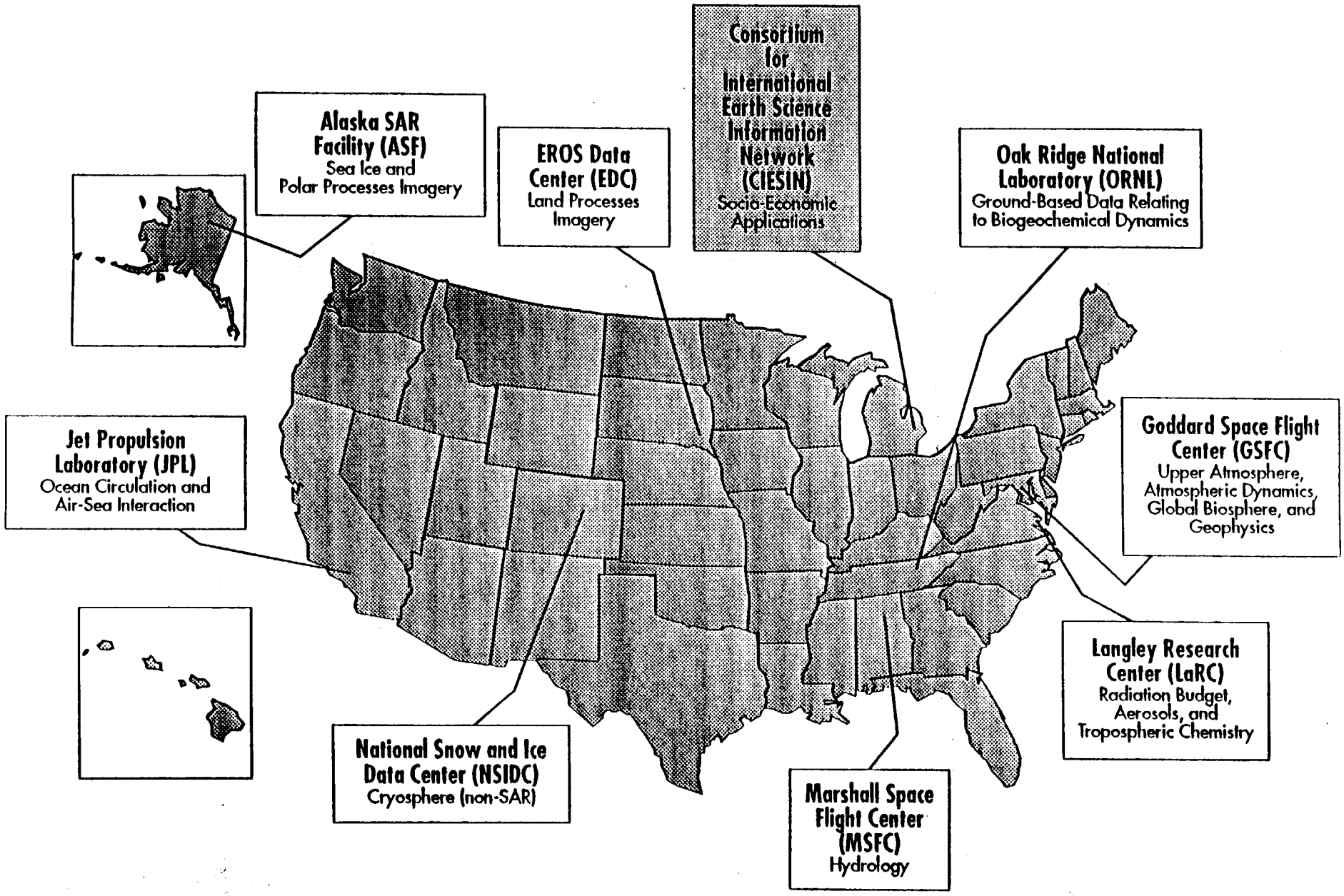
Alaska SAR Facility (ASF)
Sea Ice and Polar Processes Imagery
EROS Data Center (EDC)
Land Processes Imagery
Consortium for International Earth Science Information Network (CIESIN)
Socio-Economic Applications
Oak Ridge National Laboratory (ORNL)
Ground-Based Data Relating to Biogeochemical Dynamics
Jet Propulsion Laboratory (JPL)
Ocean Circulation and Air-Sea Interaction
Goddard Space Flight Center (GSFC)
Upper Atmosphere, Atmospheric Dynamics, Global Biosphere, and Geophysics
Langley Research Center (LaRC)
Radiation Budget, Aerosols, and Tropospheric Chemistry
National Snow and Ice Data Center (NSIDC)
Cryosphere (non-SAR)
Marshall Space Flight Center (MSFC)
Hydrology

Figure 6

Through a precursor system (i.e., Version 0), it will support research and analysis with existing data, and will establish common protocols for the transfer of data sets. By 1994, EOSDIS will provide improved access to current satellite data, along with "Pathfinder" data sets—that is, images from existing operational sensors that have been converted to geophysical and biological parameters in the prototype standard chosen for Version 0 [i.e., the Hierarchical Data Format (HDF)].

By the launch of the first EOS platform in 1998, EOSDIS will provide operational capabilities for information management, archive, and distribution. Data from the EOS space component will be processed within a few hours to a few days after observations reach the ground, depending on the level of data desired [i.e., raw data (Level 0) up to model output (Level 4)]. Researchers will then be able to cross-correlate data sets and access data easily through an information management/data distribution system, with the networking between DAACs virtually transparent to the end user.

EOSDIS will be the most important scientific contribution to Earth system science in this decade, even before monitoring from the EOS platforms begins—enabling scientists to assimilate and interpret the vast amount of existing data that are not currently being exploited. Setting the stage for the EOS missions in the late 1990s, early EOSDIS activity may well lead to important global change research breakthroughs in the near future.

2.2.3. EOS Interdisciplinary Science Investigations

In response to the EOS Announcement of Opportunity (AO) issued in 1988, 29 Interdisciplinary Science Investigation teams were selected to develop and refine models of Earth system processes. Interactions within and between these science teams will foster the development of the interdisciplinary perspective required to understanding the Earth as a system. NASA has always funded research in specific Earth science disciplines that contribute to a detailed understanding of individual processes. One of the objectives of the Interdisciplinary Science Investigations is to forge new alliances among scientific disciplines and to require scientists to enter into truly interdisciplinary teams that address global change issues.

Each investigation is led by a Principal Investigator and a team of co-investigators. Some investigations have as few as four co-investigators while others have more than 20; nine investigations are co-sponsored or solely funded by the international partners. All investigations will exploit the newly accessible data to be generated by EOS, with research results available through EOSDIS to enhance broad participation by the science community at large. The applicability of individual Interdisciplinary Science Investigations to the IPCC categories identified earlier receives attention in Chapters 4

through 10. Titles of the 29 investigations are given below to offer a flavor of the science to be gleaned from EOS observations; indepth coverage is provided in the "1993 EOS Reference Handbook" (Asrar and Dokken, 1993):

- *Coupled Atmosphere-Ocean Processes and Primary Production in the Southern Ocean*—Mark Abbott/Oregon State University
- *Global Water Cycle: Extension Across the Earth Sciences*—Eric Barron/Pennsylvania State University
- *Long-Term Monitoring of the Amazon Ecosystems through EOS: From Patterns to Processes*—Getulio Batista/Instituto Nacional de Pesquisas Espaciais (Brazil) and Jeffrey Richey/University of Washington
- *Biogeochemical Fluxes at the Ocean/Atmosphere Interface*—Peter Brewer/Monterey Bay Aquarium Research Institute
- *Northern Biosphere Observation and Modeling Experiment*—Josef Cihlar/Canada Centre for Remote Sensing (Canada)
- *NCAR Project to Interface Modeling on Global and Regional Scales with EOS Observations*—Robert Dickinson/University of Arizona
- *Hydrology, Hydrochemical Modeling, and Remote Sensing in Seasonally Snow-Covered Alpine Drainage Basins*—Jeff Dozier/University of California-Santa Barbara
- *Observational and Modeling Studies of Radiative, Chemical, and Dynamical Interactions in the Earth's Atmosphere*—William Grose/NASA Langley Research Center
- *Interannual Variability of the Global Carbon, Energy, and Hydrologic Cycles*—James Hansen/NASA Goddard Institute for Space Studies
- *Interdisciplinary Studies of the Relationships between Climate, Ocean Circulation, Biological Processes, and Renewable Marine Resources*—Graham Harris/Commonwealth Scientific and Industrial Research Organization (Australia)
- *Climate Processes Over the Oceans*—Dennis Hartmann/University of Washington
- *Climate, Erosion, and Tectonics in the Andes and Other Mountain Systems*—Bryan Isacks/Cornell University
- *The Hydrologic Cycle and Climatic Processes in Arid and Semi-Arid Lands*—Yann Kerr/Laboratoire d'Etudes et de Recherches en Télédétection Spatiale (France) and Soroosh Sorooshian/University of Arizona
- *Global Hydrologic Processes and Climate*—William Lau/NASA Goddard Space Flight Center
- *The Processing, Evaluation, and Impact on Numerical Weather Prediction of AIRS, AMSU, and MODIS Data in the Tropics and Southern Hemisphere*—John LeMarshall/Bureau of Meteorology Research Centre (Australia)
- *The Role of Air-Sea Exchanges and Ocean Circulation in Climate Variability*—W. Timothy Liu/NASA Jet Propulsion Laboratory

- *Changes in Biogeochemical Cycles*—Berrien Moore III/University of New Hampshire
- *A Global Assessment of Active Volcanism, Volcanic Hazards, and Volcanic Inputs to the Atmosphere from EOS*—Peter Mouginis-Mark/University of Hawaii
- *Investigation of the Atmosphere-Ocean-Land System Related to Climatic Processes*—Masato Murakami/Japan Meteorological Agency (Japan)
- *Chemical, Dynamical, and Radiative Interactions through the Middle Atmosphere and Thermosphere*—John Pyle/Cambridge University (United Kingdom)
- *The Development and Use of a Four-Dimensional Atmospheric-Ocean-Land Data Assimilation System for EOS*—Richard Rood/NASA Goddard Space Flight Center
- *Polar Exchange at the Sea Surface (POLES): The Interaction of Oceans, Ice, and Atmosphere*—Drew Rothrock/University of Washington
- *Using Multi-Sensor Data to Model Factors Limiting Carbon Balance in Global Grasslands*—David Schimel/Colorado State University
- *Investigation of the Chemical and Dynamical Changes in the Stratosphere Up to and During the EOS Observing Period*—Mark Schoeberl/NASA Goddard Space Flight Center
- *Biosphere-Atmosphere Interactions*—Piers Sellers/NASA Goddard Space Flight Center
- *Use of a Cryospheric System (CRYSYS) to Monitor Global Change in Canada*—Réjean Simard/Canada Centre for Remote Sensing (Canada)
- *Middle and High Latitudes Oceanic Variability Study*—Meric Srokosz/British National Space Centre (United Kingdom)
- *Earth System Dynamics: The Determination and Interpretation of the Global Angular Momentum Budget Using EOS*—Byron Tapley/University of Texas–Austin
- *An Interdisciplinary Investigation of Clouds and Earth's Radiant Energy System: Analysis*—Bruce Wielicki/NASA Langley Research Center.

2.2.4. Global Change Fellowship Program

The Graduate Student Fellowship in Global Change Research was established in 1990, to support graduate students pursuing Ph.D. degrees in Earth system science. The main objective of this program is to train the next generation of scientists and engineers to help analyze, interpret, and manage the wealth of data and information generated during the EOS era. NASA has received more than 1,000 applications since program inception, and awarded 159 fellowships in its first 3 years. The original goal was to scale up to 150 graduate students prior to the launch of EOS-AM1; however, this plateau has already been surpassed. In support of the U.S. Global Change Research

program, NASA intends to continue supporting the current fellowship recipients for a minimum of 3 years each, and to increase the total number of fellowships to 200 over the next 5 years, maintaining this level throughout the EOS mission lifetime.

2.3. SYNERGISM AND SIMULTANEITY

In the EOS science strategy, two types of synergism need to be considered—one related to instruments and the other to science. Instrument synergism implies that instruments must be grouped together, and cannot be separated without compromising the accuracy of some of the measurements. Science synergism means that groups of instruments flying together will satisfy scientific objectives broader than those addressed by the same instruments flying separately.

[Ghassem to add paragraph on science synergism....]

Simultaneity also plays a key role in the EOS observation strategy. Understanding the Earth as a system requires measurements of many variables over the whole Earth at appropriate spatial and temporal scales. Many of these measurements and interpretations require simultaneous observations of coupled phenomena. Some instruments acquire data simultaneously to provide accurate measurement of states of the surface and atmosphere; hence, multiple sensors must be placed on the same platform to observe the same phenomena.

Within the full EOS instrument suite, sets of instruments complement one another to produce desired observations (e.g., MODIS cloud observations helping interpret CERES radiation budget measurements). In some instances, certain instrument suites must generate correlative data; therefore, they must make their measurements simultaneously (e.g., DORIS providing ionospheric correction for SSALT measurements). These sets dictate some minimum payload groupings, around which alternative scenarios have been built and assessed. Chapters 4 through 10 provide more detail on these requirements.

The time scales for significant variations in the phenomena being observed define the meaning of "simultaneous." Two principal time scales prove important to this aspect of the observing strategy:

- **Time Scales of a Few Days**—Some EOS instruments need to be in orbit at the same time, to enable many of the variable components of the Earth system to be characterized globally every 1 to 3 days. This requirement spurs the extensive set of planned observing capabilities. While many aspects of the Earth do not change on the time scale of

days, all EOS instruments observe dynamic phenomena that do change rapidly.

- **Time Scales of a Few Minutes**—Changes in temperature, aerosol concentrations, water vapor distributions, and clouds can significantly affect the atmospheric contribution to signals received by optical instruments. This imposes simultaneity requirements on separate sets of instruments to make their observations within a few minutes of one another and from the same perspective.

2.4. SUMMARY

EOS is a comprehensive, multi-faceted program designed to realize the full promise of Earth system science and the global change research effort. The EOS Program combines space- and ground-based data collection and analysis with computer models of the Earth's interrelated processes; thus, the program represents a logical consequence of Earth and life science research conducted over the last 20 years. However, EOS assumes an even greater significance in that it will provide a new level of information about the integrated nature of the Earth system.

The Earth system is indeed tightly coupled, and all parts must be understood before researchers can predict changes. By collecting simultaneous observations of critical parameters of the ocean, land, and atmosphere, scientists will dramatically improve current understanding of major components of the Earth system and relevant interactions.

3.0. EOS IMPLEMENTATION

The global changes of primary concern to national and international policymakers are those that could impact the Earth's life support system.

Our Changing Planet: The FY1992 U.S. Global Change Research Program, 1991

3.1. CONTINUITY OF DATA AND EARLY MEASUREMENTS

Without a doubt, global changes have already taken place that affect the Earth's life support system; therefore, it is important that we immediately begin to gather and process data to provide insight into the status of the Earth system.

3.1.1. Historical Data

The EOS Program has begun to address global change by extending and improving existing data sets. Previous satellite and other data sets are being re-assessed in order to produce a longer baseline from which researchers can determine the rate of global change.

Critical global satellite data that reside in Federal archives have already been identified by the EOS Program as Pathfinder projects: Advanced Very High-Resolution Radiometer (AVHRR), TIROS Operational Vertical Sounder (TOVS), Geostationary Operational Environmental Satellite (GOES), Special Sensor Microwave/Imager (SSM/I), Scanning Multispectral Microwave Radiometer (SMMR), and Land Remote-Sensing Satellite (Landsat) data sets. The main goal of the Pathfinder Program is to make research-quality global change data sets easily available to the Earth science community. Certain Pathfinder products will become available as early as the fall of 1993, through EOSDIS Version 0.

These Pathfinders follow the successful reprocessing of Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) data to establish ozone trends, and Coastal Zone Color Scanner (CZCS) ocean productivity time series in anticipation of the launch of SeaWiFS and the EOS satellites. Both of these reprocessing efforts were undertaken by NASA Goddard Space Flight Center.

3.1.2. Mission to Planet Earth Phase I

NASA is responsible for Earth science missions that directly contribute to GCRP objectives in the years prior to EOS. Precursor flights considered

NASA elements of MTPE Phase I include, but are not limited to, ERBS, UARS, TOPEX/Poseidon, LAGEOS-2, Earth Probes (i.e., TOMS, NSCAT, and TRMM), SeaWiFS, Landsat-7, and Space Shuttle payloads. Select missions that have direct relevance to the EOS satellite series are described below.

UARS was launched in the summer of 1991, carrying a payload of 10 instruments that focus on the chemical, radiative, and dynamic processes of the stratosphere. In addition, UARS provides a limited set of companion measurements to assess tropospheric ozone concentrations. The EOS satellites will continue the UARS time series of data with instruments such as MLS and HIRDLS. TOMS data have also proven essential in mapping ozone depletion, particularly the Antarctic ozone hole. Data continuity will be ensured through international collaborations and by a dedicated Earth Probes mission—TOMS/Meteor-3 (Russia) and TOMS/ADEOS (Japan), and TOMS/EP94, respectively. TOMS/Meteor-3 is currently operating, and TOMS/ADEOS will be launched in February 1996; plans call for TOMS/EP94 to be launched in July 1994. Instruments such as SAGE III and MOPITT will continue stratospheric and tropospheric ozone measurements during the EOS era.

The joint NASA and Centre National d' Etudes Spatiales (CNES) TOPEX/Poseidon mission was launched in August 1992. This mission uses radar altimeters to provide precise measurements of broad-scale ocean surface currents, yielding information about the complex ocean circulatory system and its role in regulating global climate. Copies of the TOPEX/Poseidon altimeter (SSALT), microwave radiometer (TMR), and its orbit determination system (DORIS) are slated for the EOS-ALT series.

NSCAT will fly on the ADEOS satellite in 1996, providing ocean surface vector wind information. Its follow-on (NSCAT II) is being funded through the EOS Program, and will be flown on the ADEOS IIa platform in 1999. TRMM, another Earth Probe, is also a cooperative venture with the Japanese. Two EOS-funded instruments (CERES and LIS) will be onboard to study clouds, radiation, and lightning in the tropics. TRMM launch is scheduled for 1997.

Missions planned for short-term deployment on the Space Shuttle help develop new instruments, prove new technologies, continue vital data sets, and establish calibration for longer term observations. Shuttle missions planned for the near future include the Atmospheric Laboratory for Applications and Science (ATLAS), Lidar In-Space Technology Experiment (LITE), Shuttle Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR), and the Shuttle Solar Backscatter Ultraviolet (SSBUV). SSBUV addresses upper atmosphere ozone measurements for cross-calibration (i.e., via underflights of UARS), and ATLAS observes solar influences on atmospheric chemistry.

Many of the EOS instruments that fly before the launch of EOS-AM1 will support large-scale experiments as part of the World Climate Research Program (WCRP) and the International Geosphere-Biosphere Program (IGBP). TOPEX/Poseidon and NSCAT will provide essential data for the World Ocean Circulation Experiment (WOCE), and TRMM will provide precipitation data needed for the Global Energy and Water Cycle Experiment (GEWEX).

3.1.3. IEOS Partner Missions

The space- and ground-based elements of the EOS Program are not enough to completely sample the dynamic processes of the Earth. Understanding the Earth system and its long-term changes is larger and more expensive than any one nation can manage alone. EOS is part of an international research effort that encompasses space agencies, national and international scientific programs, and researchers, engineers, managers, and policymakers from around the world. The following subsections highlight the contributions of our partners in the International Earth Observing System—specifically, the Japanese ADEOS and TRMM missions, the European POEM satellites, and NOAA's POES series. Table 3 lists the missions and instruments comprising IEOS, highlighting the elements of the various satellite payloads that are being contributed via the partner nations and operational meteorological agencies. IEOS is truly an international, cooperative venture.

[Insert Table 3. IEOS: An International Partnership]

Japan

ADEOS will be launched into an 800-km, 98.6° inclined, sun-synchronous orbit by an H-II rocket in February 1996, continuing and building upon the Earth, atmospheric, and oceanographic remote-sensing measurements initiated by the Marine Observation Satellite (MOS) series and JERS-1. The sensors on ADEOS include two developed by Japan, plus six AO instruments provided by other agencies and partner nations. Core sensors developed by NASDA include the Ocean Color and Temperature Scanner (OCTS) and the Advanced Visible and Near-Infrared Radiometer (AVNIR). AO instruments include the Interferometric Monitor for Greenhouse Gases (IMG) developed by the Ministry of International Trade and Industry (MITI); the Improved Limb Atmospheric Spectrometer (ILAS) and the Retroreflector in Space (RIS) developed by the Environment Agency of Japan (EAJ); the Polarization and Directionality of Earth's Reflectances (POLDER) provided by CNES; and NSCAT and TOMS provided by NASA.

OBJECTIVES	PROPOSED INSTRUMENT CONFIGURATION													
	ADEOS 799.8 km 10:30 a.m. 1Q 1996	NOAA-K 1:30 p.m. Polar 2Q 1996	NOAA-L 7:30 a.m. Polar 2Q 1997	TRMM-1 350 km 35° Inclination 3Q 1997	EOS-AM1 705 km 10:30 am 2Q 1998	EOS-COLOR Polar 1998	ADEOS II Polar 1999	POEM-ENVISAT1 1998	NOAA/N/N' PM/PM/PM Polar 1999, 2000, 2002	EOS-AERO1 57° Inclination 2Q 2000	EOS-PM1 705 km 1:30 pm 4Q 2000	POEM-METOP1 2000	EOS-ALT1 Polar 1Q 2002	EOS-CHEM1 Polar 3Q 2002
VIS/IR Images	OCTS, AVNIR, POLDER	AVHRR-3	AVHRR-3	VIRS, LIS	MODIS, ASTER, MISR	Data Purchase	GLI	AATSR, MERIS	AVHRR-3		MODIS	AATSR, AVHRR-3		
Radiation Budget	POLDER			CERES	CERES (dual)			SCARAB			CERES (dual)	SCARAB		
Passive Atmospheric Sounding		AMSU-A1/2, AMSU-B, HIRS-3	AMSU-A1/2, AMSU-B, HIRS-3				AMSR		AMSU-A1/2, AMSU-B, HIRS-3		AIRS, AMSU, MHS	AMSU-A1/2, MHS, IASI, HIRS-3		
Passive Microwave				TMI			AMSR				MIMR	MIMR		
Active Microwave	NSCAT			PR			NSCAT II	ASAR				ASCAT	TMR	
Tropospheric Chemistry	IMG				MOPITT		IMG-2	SCIAMACHY					GLAS	HIRDLS
Stratospheric Chemistry	TOMS, ILAS	SBUV-2						GOMOS, SCIAMACHY, MIPAS	SBUV-2	SAGE III		GOMI		SAGE III, HIRDLS, MLS
Tropospheric Wind Lidar														
Altimeter								RA-2					SSALT	
Laser Ranging and Sounder													GLAS	
Other	RIS				DAS			PRAREE			DAS	MCP, DCS	DORIS	SOLSTICE II, ACRIM
Operational Instruments		AVHRR-3, AMSU-A1/2, AMSU-B, HIRS-3, SBUV-2, SEM, ARGOS, S&R	AVHRR-3, AMSU-A1/2, AMSU-B, HIRS-3, SEM, ARGOS, S&R						AVHRR-3, AMSU-A1/2, AMSU-B, HIRS-3, SBUV-2, SEM, ARGOS, S&R			AVHRR-3, AMSU-A1/2, MHS, S&R, ARGOS+, SEM, HIRS-3		

= International Contributions to Partner Nation Platforms

2 Table 3

TRMM is a joint NASA/NASDA mission with the sole objective of measuring precipitation—undoubtedly the most difficult atmospheric variable to quantify, and the crucial driver of the hydrologic cycle and atmospheric dynamics. TRMM will measure diurnal variation of latent heating and convective processes in the tropics from a 350-km, 35° inclined orbit using the following sensors: CERES, LIS, Precipitation Radar (PR), TRMM Microwave Imager (TMI), and Visible Infrared Scanner (VIRS). Japan provides PR and the launch aboard an H-II rocket in August 1997; NASA will provide the spacecraft, the rest of the payload, and instrument integration.

The conceptual design of an ADEOS follow-on—ADEOS II—is still underway. One proposal calls for dividing ADEOS II into two separate missions (i.e., ADEOS IIa and IIb), with the first satellite to be launched in 1999. ADEOS IIa would carry a global monitoring payload emphasizing the hydrologic cycle, while ADEOS IIb would have high-resolution visible and microwave sensors. Both satellites would have orbital specifications similar to the ADEOS mission. AMSR and GLI will be the core global imaging sensors for ADEOS IIa, complemented by IMG-2 and NSCAT II. The entire ADEOS IIb payload—consequently its launch date—has yet to be determined. Strong candidates for ADEOS IIb include a next-generation version of AVNIR and a radar to ensure continuity with SAR data provided by JERS-1.

Table 4 offers a list of the instruments to be flown by Japan, with brief measurement objectives appended.

[Insert Table 4. Japanese Instruments Planned as Part of IEOS]

Europe

The POEM satellites will make comprehensive research and operational observations of the Earth. POEM will be implemented as two spacecraft series—one for environmental monitoring and atmospheric chemistry (ENVISAT), and one for operational meteorological and climate monitoring (METOP). Both satellites will use the *Columbus* polar platform, and both will be equipped to work with the European Data Relay Satellite System (DRSS).

POEM-ENVISAT has the dual objectives of continuing ERS measurements and contributing to environmental studies in land surface properties, atmospheric chemistry, aerosol distribution, and marine biology. The instrument package consists of five ESA-funded instruments and four instruments to be provided by individual ESA member states. The ESA facility instruments include the Advanced Synthetic Aperture Radar (ASAR), Global Ozone Monitoring by Occultation of Stars (GOMOS), Medium-Resolution Imaging Spectrometer (MERIS), Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), and Radar Altimeter (RA-2), which

	Instrument	Category	Measurement Objective
ADEOS	AVNIR	VIS/IR Images	Solar light reflected by the Earth's surface
	OCTS	VIS/IR Images	Ocean color and sea surface temperature
	ILAS	Stratospheric Chemistry	Stratospheric ozone and related species at high latitudes
	IMG	Tropospheric Chemistry	Carbon dioxide, methane, and other greenhouse gases
	NSCAT	Active Microwave	Wind speed and direction over the oceans
	POLDER	VIS/IR Images and Radiation Budget	Atmospheric aerosols
	RIS	Atmospheric Chemistry	Atmospheric trace gases
	TOMS	Stratospheric Chemistry	Daily global ozone observations
TRMM	CERES	Radiation Budget	Radiation budget
	LIS	VIS/IR Images	Distribution and variability of lightning over the Earth
	PR	Active Microwave	Three-dimensional profiles of rain rates in the tropics
	TMI	Passive Microwave	Precipitation measurements
	VIRS	VIS/IR Images	Variations of rainwater content with altitude
ADEOS IIa	AMSR	Passive Atmospheric Sounding and Passive Microwave	Precipitation, water vapor distribution, cloud water, sea surface temperature, sea ice, and sea surface wind speed
	GLI	VIS/IR Images	Biological/physical processes and stratospheric ozone
	IMG-2	Tropospheric Chemistry	Carbon dioxide, methane, and other greenhouse gases
	NSCAT II	Active Microwave	Ocean surface vector winds
Candidates for ADEOS IIb	ADALT	Altimeter	Geoid, ocean waves, and polar ice
	AVNIR+	VIS/IR Images	Upwelling radiance in multiple spectral bands
	E-LIDAR	Laser Ranging and Sounding	Aerosol and cloud vertical profiles of water vapor, and ice sheet and sea level
	IMB	VIS/IR Images	Ecological environment measurements with high spatial resolution
	PR-2	Active Microwave	Three-dimensional measurement of global rain rate
	SLIES	Stratospheric Chemistry	Infrared emissions of stratospheric and tropospheric minor species
	TERSE	Tropospheric Chemistry	Global monitoring of tropospheric chemistry profiles
	TOMUIS	Stratospheric Chemistry	Three-dimensional mapping of stratospheric ozone distribution

Table 4

Core Instruments

includes a microwave sounder. The following national contributions are also included on the POEM-ENVISAT manifest: Advanced Along-Track Scanning Radiometer (AATSR), Precise Range and Range Rate Equipment—Extended (PRAREE), Scanner for the Radiation Budget (SCARAB), and Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY). The first POEM-ENVISAT launch is scheduled for mid-1998, with the launch of a second planned for 2003.

POEM-METOP will fly an operational meteorological package in cooperation with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and NOAA. This series will take over morning operational satellite coverage from the NOAA POES system in 2000. This collaborative venture has the current objective of operational meteorology and climate monitoring, and a future objective of operational climatology. A preparatory program for METOP was approved at the November 1992 ESA Ministerial Conference. The complete payload will be determined in 1994, when final program approval and funding is expected. The core operational meteorology payload consists of six instruments: AMSU-A1/2, AVHRR-3, Data Collection System (DCS), High-Resolution Infrared Sounder (HIRS-3), Infrared Atmospheric Sounding Interferometer (IASI), and MHS. The operational meteorological package also includes Meteorological Communications Package (MCP), Search and Rescue (S&R), and Space Environment Monitor (SEM). In addition, the following instruments have been proposed for climatological monitoring: Advanced Scatterometer (ASCAT), AATSR, Global Ozone Monitoring Instrument (GOMI), MIMR, and SCARAB.

Table 5 lists the instruments and measurement objectives proposed by Europe as contributions to IEOS.

[Insert Table 5. European Instruments Planned as Part of IEOS]

The National Oceanic and Atmospheric Administration

NOAA conducts U.S. civil programs for operational Earth remote sensing. The current and future satellites of the POES series are an essential part of IEOS, since these satellites provide valuable precursor data and will yield complementary observations during the EOS mission lifetime. NOAA's long-term data record is already being used to establish baseline conditions and to detect trends, with several NASA/NOAA Pathfinder projects underway (i.e., reprocessing of AVHRR, TOVS, and GOES data).

The present POES Program maintains two operational satellites in polar orbit—one providing morning (AM) coverage and the other afternoon (PM) coverage. The U.S. and Europe (i.e., EUMETSAT and ESA) have agreed that

	Instrument	Category	Measurement Objective
POEM-ENVISAT	ASAR	Active Microwave	All-weather imaging of land surfaces, coastal zones, sea ice, and ice- and snow-covered surfaces
	GOMOS	Stratospheric Chemistry	Global ozone monitoring
	MERIS	VIS/IR Images	Ocean color and biological components (carbon cycle)
	MIPAS	Stratospheric Chemistry	Composition, dynamics, and radiation balance of the middle and upper troposphere
	RA-2	Altimeter	Significant wave height and sea level determination, ocean circulation (dynamics), ice sheet topography, and land mapping
	AATSR	VIS/IR Images	Sea surface temperature and land-surface measurements for ocean dynamics and radiation interaction studies
	PRAREE	Altimeter	Orbitography, geodesy, plate tectonics, and ocean topography
	SCARAB	Radiation Budget	Global measurements of the radiation budget
	SCIAMACHY	Stratospheric and Tropospheric Chemistry	Total concentration and vertical distribution of atmospheric trace gas species, temperature, and aerosols in the troposphere and stratosphere
POEM-METOP	AMSU-A1/2	Passive Atmospheric Sounding	Global temperature profiles from ground level to 45 km
	AVHRR-3	VIS/IR Images	Global monitoring of clouds, sea surface temperature, vegetation, and ice
	DCS	Data Relay (ARGOS+)	Relays data from over 4,000 collection platforms worldwide
	HIRS-3	Passive Atmospheric Sounding	Global atmospheric temperature profiles, atmospheric water content, and cloud properties
	IASI	Passive Atmospheric Sounding	Atmospheric temperature and humidity profiles, and continuous monitoring of global radiation, dynamics, and energy flux
	MHS	Passive Atmospheric Sounding	Precipitation and water vapor profiles
	ASCAT*	Active Microwave	Ocean surface wind speed and direction, and ocean circulation and dynamics
	AATSR*	VIS/IR Images	Sea surface temperature and land-surface measurements for ocean dynamics and radiation interaction studies
	GOMI*	Stratospheric Chemistry	Global ozone distributions from both solar radiation backscatter and differential optical absorption spectroscopy
	MCP	Data Relay	Direct data handling and broadcast of operational instrument data streams to ground stations
	MIMR*	Passive Microwave	Precipitation rate, cloud water, water vapor, sea surface roughness, sea surface temperature, ice, snow, and soil moisture
	S&R	Data Relay	Receives beacon signals, and transmits in real-time to ground stations around the world
	SCARAB*	Radiation Budget	Global measurements of the radiation budget
	SEM	Other	Monitors particles and fields to measure/predict solar events

*Proposed Climatological Monitoring Instruments

Table 5

Core Instruments

Europe will take over responsibility for the AM global coverage mission in the year 2000, and that NOAA will continue PM coverage indefinitely. Through NOAA, the U.S. will provide a suite of four primary sensors for the European AM mission: AMSU-A1/2, AVHRR-3, HIRS-3, and SEM (see the European section for descriptions of these instruments). EUMETSAT and others will reciprocate by supplying sensors and subsystems for flight on both the NOAA-L (morning) and -K/M/N/N' (afternoon) satellites.

Long-term improvements in NOAA satellite, instrument, and space subsystem design are expected to result from technology advances associated with the EOS Program. To this end, coordination in technology development extends to NASA designating some EOS instruments as "prototypes" for future operational environmental satellites. This means that NOAA and NASA are agreeing on design features that would enable these prototypes to be transferred to NOAA spacecraft after being space-proven in NASA research/demonstration efforts.

3.2. THE EOS ERA

3.2.1. Instruments and Measurement Strategy

Scientific priorities having been determined, and the strategy for addressing them developed, implementation requires launching several suites of instruments into orbit—each designed to accomplish a critical portion of the mission. Within the larger scheme of USGCRP, EOS will build on the investments made in the Earth observations satellites comprising MTPE Phase I, providing better measurements of critical Earth system processes. Figure 7 provides the launch profile for the EOS series through 2005, and Table 6 summarizes the measurement objectives of each of the EOS satellite series.

[Insert Figure 7. EOS Mission Launch Profile here]
[Insert Table 6. The EOS Satellite Series here]

Synergistic instrument clusters have been identified that address specific scientific problems (e.g., role of clouds in climate). To the extent that instrument clusters can be accommodated on the same spacecraft, errors caused by temporal variability in observed phenomena are minimized. This is particularly significant for removing the effects of the intervening atmosphere from measurements of reflectance or emittance from the Earth's surface made by passive optical sensors.

EOS-AM

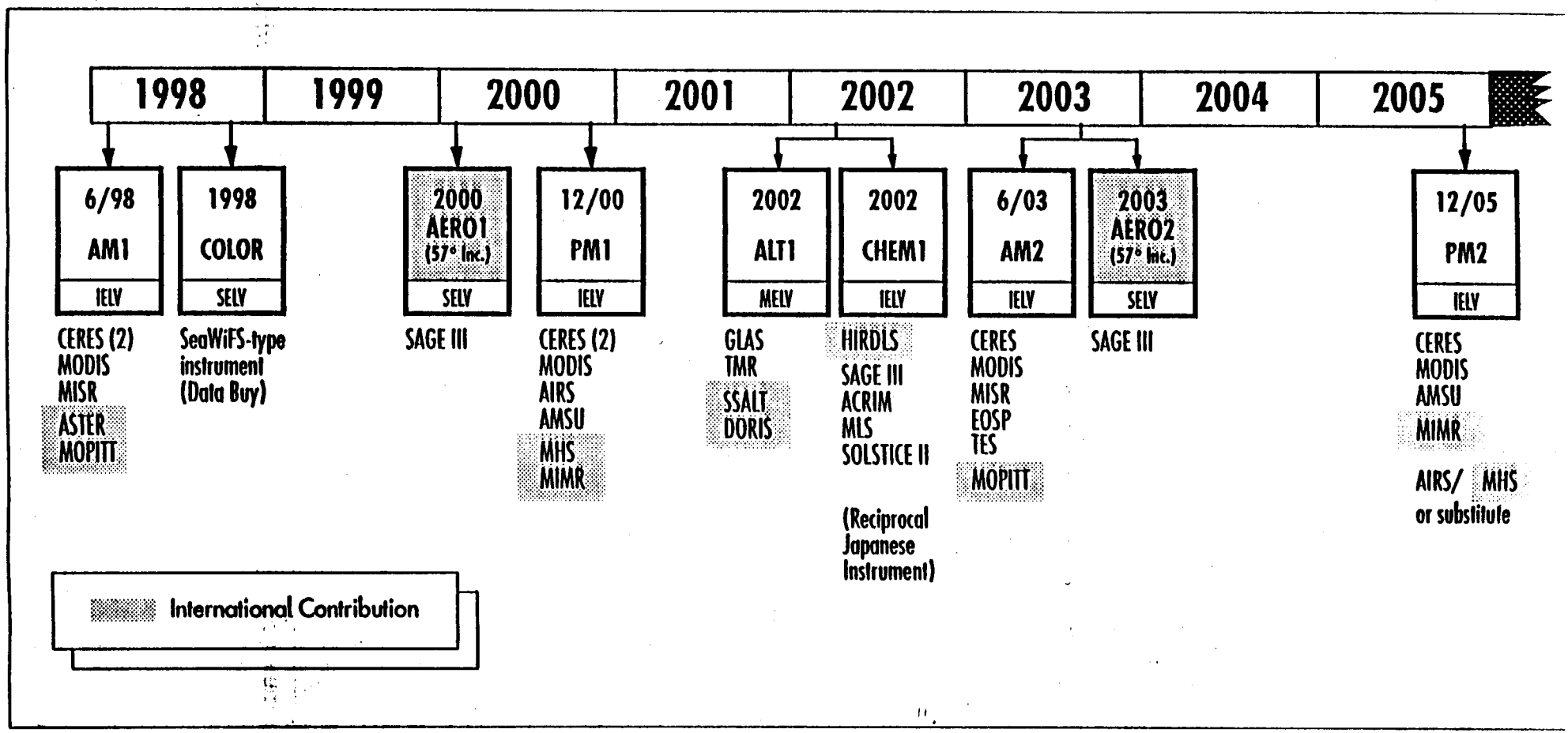
1998
1999
2000
2001
2002
2003
2004
2005
6/98
AM1
IELV
CERES (2)
MODIS
MISR
ASTER
MOPITT
1998
COLOR
SELV
SeaWiFS-type
instrument
(Data Buy)
2000
AERO1
(57° Inc.)
SELV
SAGE III
12/00
PM1
IELV
CERES (2)
MODIS
AIRS
AMSU
MHS
MIMR
2002
ALT1
MELV
GLAS
TMR
SSALT
DORIS
2002
CHEM1
IELV
HIRDLS
SAGE III
ACRIM
MLS
SOLSTICE II
(Reciprocal
Japanese
Instrument)
6/03
AM2
IELV
CERES
MODIS
MISR
EOSP
TES
MOPITT
2003
AERO2
(57° Inc.)
SELV
SAGE III
12/05
PM2
IELV
CERES
MODIS
AMSU
MIMR
AIRS/ MHS
or substitute
International Contribution

Figure 7

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Satellites (Launch Status)	Mission Objectives
EOS-AM Series (1998) Earth Observing System Morning Crossing (Descending)	Clouds, aerosols and radiation balance, characterization of the terrestrial ecosystem; land use, soils, terrestrial energy/moisture, tropospheric chemical composition; contribution of volcanoes to climate, and ocean primary productivity (includes Canadian and Japanese instruments)
EOS-COLOR (1998) EOS Ocean Color Mission	Ocean primary productivity
EOS-PM Series (2000) Earth Observing System Afternoon Crossing (Ascending)	Cloud formation, precipitation, and radiative properties; air-sea fluxes of energy and moisture; sea-ice extent; and soil moisture and snow over land (includes European instruments)
EOS-AERO Series (2000) EOS Aerosol Mission	Distribution of aerosols and greenhouse gases in the lower stratosphere (spacecraft to be provided through international cooperation)
EOS-ALT Series (2002) EOS Altimetry Mission	Ocean circulation and ice sheet mass balance (includes French instruments)
EOS-CHEM Series (2002) EOS Chemistry Mission	Atmospheric chemical composition; chemistry-climate interactions; air-sea exchange of chemicals and energy (to include an as yet to be determined Japanese instrument)

Table 6

Measurement of the diurnal properties of clouds and radiative fluxes requires observations in morning and afternoon sun-synchronous orbits, as well as the inclined orbits provided by TRMM and the EOS-AERO series. Another group of instruments on the morning spacecraft will address issues related to the land surface-atmosphere exchanges of energy, carbon, and water—a task that is addressed now only qualitatively by AVHRR and Landsat. EOS-AM1 will have an equatorial crossing time of 10:30 a.m., when daily cloud cover is typically at a minimum over land such that surface features can be more easily observed. The instrument complement is intended to obtain information about the physical and radiative properties of clouds (ASTER, CERES, MISR, MODIS); air-land and air-sea exchanges of energy, carbon, and water (ASTER, MISR, MODIS); vertical profiles of important greenhouse gases (MOPITT); and the role of volcanoes in the climate system (ASTER, MISR, MODIS). CERES, MISR, and MODIS are provided by the U.S.; MOPITT is provided by Canada; and ASTER is provided by Japan.

The mission includes three AM flights—EOS-AM1 to be launched in June 1998, EOS-AM2 in June 2003, and EOS-AM3 in June 2008. Since the EOS-AM1 spacecraft is unique, changes in the follow-on flights have already been scheduled. MODIS, MISR, and CERES remain onboard EOS-AM2, though CERES will carry only a single scanner on the follow-on AM platforms. Negotiations are still underway to accommodate MOPITT on EOS-AM2. TES and EOSP, both of which provide tropospheric aerosol and chemistry data, will replace ASTER, which will only fly on the EOS-AM1 satellite. With the possible exception of MOPITT, EOS-AM3 is expected to have the same payload as EOS-AM2.

EOS-PM

The EOS-PM series spacecraft will have an afternoon crossing time to enhance collection of meteorological data by the atmospheric sounders onboard. The instrument complement is designed to provide information on cloud formation, precipitation, and radiative properties via AIRS, AMSU, CERES, MHS, and MODIS. In concert with vector wind stress measurements from a scatterometer (e.g., NSCAT II on ADEOS), MIMR, AIRS/AMSU/MHS, and MODIS will provide data for global-scale studies of air-sea fluxes of energy, moisture, and momentum. In addition, MIMR, MODIS, and AIRS will contribute to studies of sea-ice extent and heat exchange with the atmosphere. Flight of this platform during the operational lifetime of TRMM will allow assessment of the utility and accuracy of precipitation estimates based on MIMR data, with MODIS and MIMR mapping the extent and properties of snow and its role in the climate and hydrological systems. AIRS, AMSU, CERES, and MODIS are provided by the U.S.; MHS is provided by EUMETSAT; and MIMR is provided by ESA.

Currently, the plan is for all EOS-PM satellites to be identical, except that CERES will consist of two scanners on EOS-PM1 and a single scanner on the follow-on flights. EOS-PM1 is scheduled for launch in December 2000, EOS-PM2 in December 2005, and EOS-PM3 in December 2010.

The morning observatory is scheduled to launch before the afternoon platform for several reasons: 1) The EOS-AM series will yield important measurements of both clouds/radiation and surface characteristics, and 2) it is more straightforward to execute than the EOS-PM1 observatory. The EOS-AM1 spacecraft includes only one challenging U.S.-furnished instrument (i.e., MODIS), whereas EOS-PM1 includes MODIS and AIRS, both of which are technologically demanding. The balance between scientific requirements, cost, schedule, and risk associated with EOS-AM1 versus -PM1 resulted in a decision to launch the morning platform first.

EOS-AERO

Current plans call for the use of an internationally contributed spacecraft to be placed into a 57° inclined, 705-km (or slightly lower) orbit to optimize collection of occultation data in the equatorial latitudes. This series involves five spacecraft launched on 3-year centers to provide the required 15-year coverage. The follow-on flights are scheduled for 2003, 2006, 2009, and 2012. SAGE III is capable of making long-term trend measurements of aerosols, ozone, water vapor, and clouds from the middle troposphere through the stratosphere—important parameters for radiative and atmospheric chemistry models.

In addition, a companion instrument may be added—either EOSP to measure sulfate aerosols, or ACRIM to measure solar irradiance at the top of the atmosphere.

EOS-COLOR

The oceans' role in world climate has been identified as the second highest priority issue to be investigated by EOS. EOS-COLOR involves a one-time acquisition of ocean primary productivity observations via a data purchase, as will be done for SeaWiFS, which is scheduled for launch onboard SeaStar in 1994. Scheduled for launch in 1998, EOS-COLOR will provide ocean color and productivity observations, with a specific focus on understanding the oceans' role in the global carbon cycle. This mission will provide data continuity until both MODIS instruments are flying. MODIS redundancy on EOS-AM1 and -PM1 will yield complete global ocean color measurements by avoiding sun-glint over the northern oceans and the lack of illumination over the southern oceans.

Variations in absorption of solar radiation by oceans caused by changes in bio-optical properties will be investigated by EOS-COLOR. Along with vector winds from a scatterometer, these measurements will allow more accurate estimates of ocean-atmosphere exchanges of carbon.

EOS-ALT

The instrument complement for the EOS-ALT mission remains intact throughout the series. EOS-ALT consists of GLAS, TMR, DORIS, and SSALT—the former two are U.S. instruments and the latter two are provided by France. In addition to precise orbit tracking (DORIS, TMR) and altimeter calibration and orbit determination (SSALT), the EOS-ALT series will provide measurements of sea ice and glacier surface topography, cloud heights, and aerosol vertical structure (GLAS). Investigation of ice sheets, relevant to sea level changes, requires accurate altimeter measurements. SSALT is a dual-frequency radar altimeter for accurate determination of ocean-surface topography, from which circulation can be inferred; GLAS is a laser altimeter that will generate accurate profiles, which are particularly needed to establish the changes in volume of the ice sheets in Greenland and Antarctica. DORIS enables the precise positioning of the spacecraft needed to interpret measurements obtained by both of these instruments. The EOS-ALT missions are scheduled for launches in the years 2002, 2007, and 2012.

EOS-CHEM

The instrument complement for EOS-CHEM currently consists of ACRIM, HIRDLS, MLS, SAGE III, SOLSTICE II, and an as yet to be determined Japanese contribution. The latter instrument is being accommodated as reciprocation for the flight of NSCAT II on ADEOS II. EOS-CHEM instruments will provide measurements of solar energy flux (ACRIM); solar ultraviolet radiation (SOLSTICE II); atmospheric aerosols, ozone, and water vapor (SAGE III); atmospheric trace gases (HIRDLS); and ozone, based on chlorine monoxide, bromine oxide, and water vapor (MLS). HIRDLS, SAGE III, and MLS on the EOS-CHEM spacecraft—along with MOPITT on EOS-AM1 (and possibly -AM2) and SAGE III on EOS-AERO—provide critical data related to tropospheric and lower stratospheric chemistry and dynamics, including troposphere-stratosphere exchanges. The EOS-CHEM flights are scheduled for 2002, 2007, and 2012.

Other EOS-Funded Instruments

Other instruments funded through the EOS Program receive their flight opportunities aboard international partner platforms. CERES and LIS in an inclined orbit on TRMM will improve diurnal coverage in conjunction with CERES on the AM and PM polar-orbiting satellites. NSCAT II has been selected as part of the ADEOS II payload. Refer back to the Japan subsection above for brief coverage of these instruments' measurement objectives.

3.2.2. EOS Science Priorities

EOS is a long-term program, providing continuous observations of global climate change; therefore, the planned payload scenarios for the years beyond 2003 focus on re-flying the basic clusters from the EOS-AM1 and -PM1 spacecraft at least twice, at 5-year intervals. The payloads on the follow-on EOS spacecraft could be modified as scientific understanding of global change evolves and technology improves. With this in mind, the scientific areas of importance discussed in Chapter 2 and their linkage to the current EOS instruments are provided as Table 7.

[Insert Table 7. Science Questions and Instrument Priorities here]

Decisions about instruments to fly on follow-on spacecraft need not be made immediately, but technology development efforts must continue to ensure that such next-generation instruments are available when needed.

3.2.3. Using EOSDIS

EOSDIS is central to the EOS Program, because it provides the environment in which scientists and other users exploit EOS and other Earth observations data and information. The design can be best characterized as flexible and resilient, while the implementation will be incremental and evolutionary. EOSDIS includes several distinct but interrelated components (see Figure 8):

- **The Flight Operations Segment**—Consisting of the EOS Operations Center (EOC) and Instrument Control Facilities (ICFs), this segment provides mission and instrument planning, scheduling, control, and monitoring. Instrument Support Terminals (ISTs) will provide capabilities for instrument command and control at the investigator's home facility; interfaces with international partners are also provided.
- **The Science Data Processing Segment**—This segment consists of the Distributed Active Archive Centers (DAACs), which includes a Product Generation System (PGS), a Data Archive and Distribution System (DADS), and an Information Management System (IMS). The primary purpose of this segment is to process higher level data from measurements taken by the instruments for scientific investigations.

Water & Energy Cycles	Oceans	Tropospheric Chemistry	Land-Surface Hydrology/Ecology
CERES	NSCAT II	TES	MODIS
MODIS	MODIS	MOPITT	MIMR
AIRS/AMSU/MHS	SSALT/DORIS/TMR	SAGE III	ASTER
MIMR	MIMR	HIRDLS	MISR
MISR	AIRS/AMSU/MHS	MLS	
EOSP	EOS-COLOR		

Ice Sheets & Glaciers	Stratospheric Chemistry	Solid Earth
GLAS/DORIS	HIRDLS	ASTER
MODIS	SAGE III	GLAS
ASTER	MLS	MISR
SSALT	SOLSTICE II	MODIS

Table 7

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- **Science Computing Facilities (SCFs)**—SCFs are located at investigator sites, and are used to develop and maintain data processing software, to produce special data products, to validate data products, and to perform scientific analyses.
- **EOS Data Operations System (EDOS)**—This system processes Level 0 data, archives them, distributes Level 0 data to the DAACs, and provides a command and telemetry interface to the Tracking and Data Relay Satellite System (TDRSS), which receives the data directly from the spacecraft.
- **Communications and System Management Segment**—This segment consists of the System Management Center (SMC) and the EOSDIS Science Network, and provides general management and coordination of the ground system resources.

[Insert Figure 8. EOSDIS Architecture here]

Achieving the goals of the overall mission will depend on how well EOSDIS helps scientists access and use reliable large-scale data sets of geophysical and biological processes under study, and on how successfully EOS scientists interact with other investigators in furthering Earth system science. Currently, progress in use of remote-sensing data for science is hampered by the need for scientists to understand too many operational details. EOSDIS, by contrast, is committed to provide immediately relevant information to a wide range of users, bypassing this operational bottleneck. Data availability is also important to users; therefore, EDOS will generate Level 0 products within 24 hours of observation, and quick-look data 6 hours thereafter for select instruments.

Standard data products will give the user community access to independent measurements to validate and drive models of processes at local, regional, and global scales. EOSDIS will include algorithms for generating the products, descriptors of data quality, and the identity of the responsible scientists. Specialized products created by EOS scientists in their own computing facilities will also be archived and distributed by EOSDIS.

An EOS data processing and distribution system requires an evolutionary, distributed design, because needs for the data will be changing, as will available hardware and software. An EOS investigator responsible for a standard data product through the life of the mission will make a major commitment to maintain algorithms and software as the instrument and environment changes, as well as to control quality and validate products. The investigator must also provide additional information enabling others to use the products. EOSDIS policy requires that all data and derived products be available to all users. No preference will be given to EOS investigators, nor will there be any period of proprietary restriction.

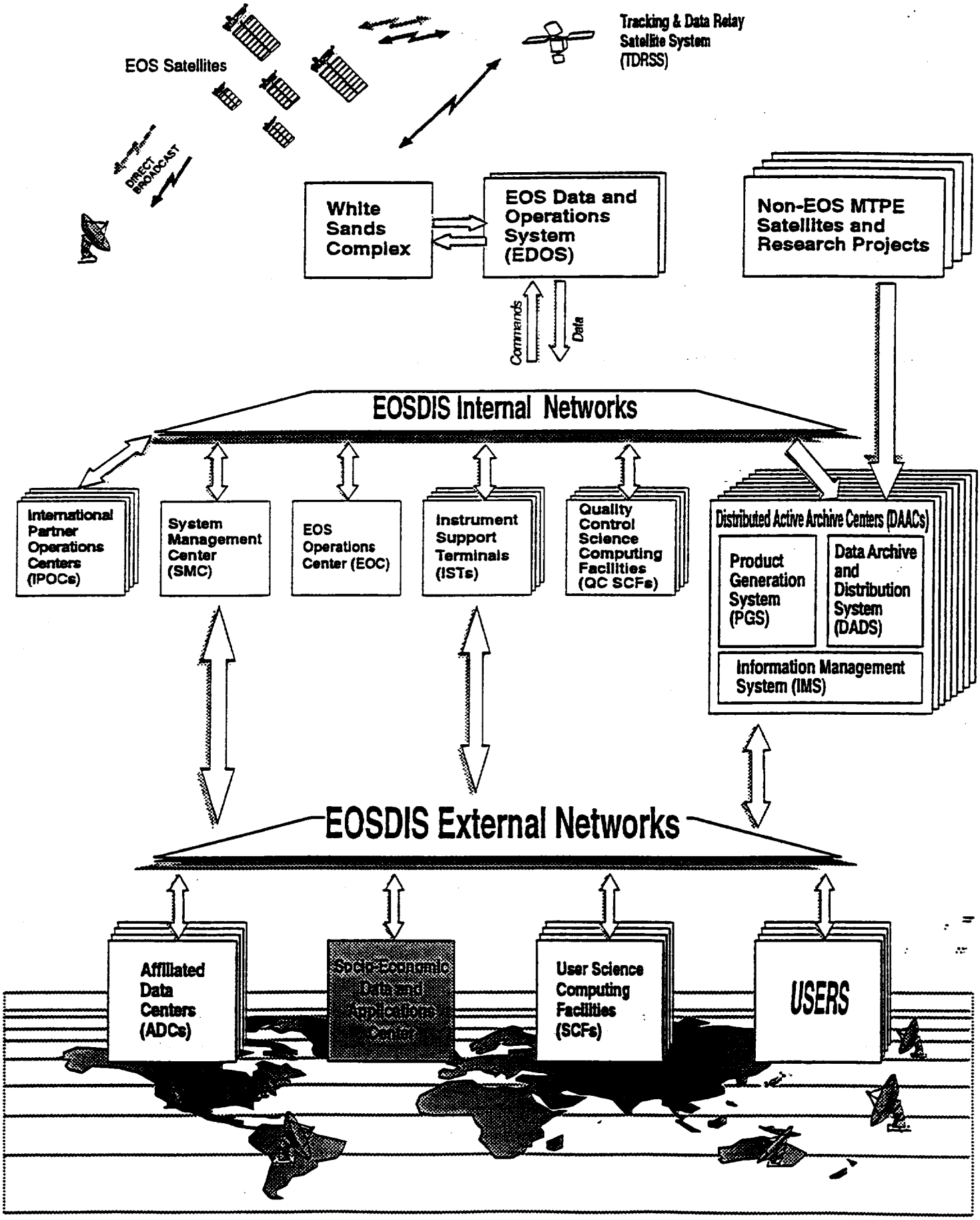
EOS Satellites
Tracking & Data Relay Satellite System (TDRSS)
DIRECT BROADCAST
White Sands Complex
EOS Data and Operations System (EDOS)
Non-EOS MTPE Satellites and Research Projects
Commands
Data
EOSDIS Internal Networks
International Partner Operations Centers (IPOCs)
System Management Center (SMC)
EOS Operations Center (EOC)
Instrument Support Terminals (ISTs)
Quality Control Science Computing Facilities (QC SCFs)
Distributed Active Archive Centers (DAACs)
Product Generation System (PGS)
Data Archive and Distribution System (DADS)
Information Management System (IMS)
EOSDIS External Networks
Affiliated Data Centers (ADCs)
Socio-Economic Data and Applications Center
User Science Computing Facilities (SCFs)
USERS

Figure 8

Users in the U.S. and participating countries will pay only the marginal costs for data reproduction and distribution, and must agree to publish their results in the open literature and make available supporting information. Users in non-participating countries may have the same access by proposing cooperative projects and associated contributions. To the extent possible, the same policies will be applied to other relevant data that are not generated by EOS, such as observations acquired by other Federal agencies participating in USGCRP or from the international partner platforms.

DAACs will fulfill the processing needs of the system, except for algorithm development and the investigations of individual scientists. Eight DAACs will ensure that data will be available indefinitely in an easily usable form. DAAC assignments were based primarily on the current distribution of scientific expertise and institutional heritage and capability (see Table 8). An additional center (i.e., CIESIN) receives funding from NASA to serve the socio-economic and educational user community. Each of these centers will provide instrument support software that will allow investigators to issue commands for instrument pointing and data acquisition. The basic idea is that multiple facilities and generic classes of data centers can best fulfill the needs of the Earth system science user community.

[Insert Table 8. EOSDIS-Sponsored Data Center Responsibilities]

EOSDIS will come to life with the advent of Version 0 between 1991 and 1994. Version 0 will use existing data from Earth Probes and other non-EOS data sources to test out issues such as development of common data formats, interoperability, and user interfaces. Version 0 development focuses on the Science Data Processing Segment described above. As EOSDIS evolves, it will subsume the capabilities of Version 0. Obviously, user needs for EOSDIS will become more clearly understood as researchers work with and respond to the earlier versions of the system. User needs will change over time. To succeed over its lifetime, EOSDIS must be responsive to this change.

Version 0 will provide the user community with improved access to Earth science data without degrading their existing services. It will also serve as an essential prototyping system for further development of EOSDIS. By 1998, the full EOSDIS system will be operational, receiving data from EOS spacecraft through the TDRSS satellite, while continuing to maintain and process data from other missions.

Storage requirements for EOSDIS will vary according to EOS satellite, from a maximum of 673 GB/day for EOS-AM to 2 GB/day for the EOS-COLOR mission. Processing requirements will vary similarly from 250 MFLOPS for EOS-PM to 21 for EOS-AERO, and even less for other non-EOS missions (see Table 9). As EOSDIS becomes fully operational, it will evolve into a significant tool, bringing Earth system science to its potential as a new field of

Distributed Active Archive Centers

Center	Discipline Responsibilities	EOS and Other Missions/Instruments
GSFC Goddard Space Flight Center	Upper atmosphere, atmospheric dynamics, global biosphere, and geophysics	AIRS/AMSU/MHS, CZCS, GLAS, HIRDLS, MIMR, MLS, MODIS, SAGE III, SeaWiFS, TOMS, and TMI
LaRC Langley Research Center	Radiation budget, aerosols, and tropospheric chemistry	ACRIM, ASTER, CERES, EOSP, ERBE, MOPITT, MISR, SAGE III, SOLSTICE II, and TES
EDC EROS Data Center	Land processes imagery	ASTER, AVHRR, Landsat (MSS and TM), MISR, SAR (land), and airborne sensors
UAF University of Alaska—Fairbanks	Sea ice and polar processes imagery	ERS-1, JERS-1, ERS-2, Radarsat, and ongoing role as ground station
CU University of Colorado	Cryosphere (non-SAR)	DORIS, GLAS, MIMR, SSALT, OLS, SMMR, and SSM/I
JPL Jet Propulsion Laboratory	Ocean circulation and air-sea interactions	MIMR, NSCAT, Seasat, SSALT, and TMR
MSFC Marshall Space Flight Center	Hydrology	MIMR, TMI, PR, LIS, and SSM/I
ORNL Oak Ridge National Laboratory	Biogeochemical dynamics	*In situ* trace gas and gas flux data
Socio-Economic Data and Applications Center		
CIESIN Consortium for International Earth Science Information Network	Human dimensions of global change and policymaking applications	Socio-economic data

Table 8

study. Since the development of predictive models is at the heart of the EOS project, the modeling capabilities supported by EOSDIS are essential. The current focus of EOS model-builders is on creating comprehensive climate models and carbon cycle models, consistent with the project's emphasis on climate-related issues.

[Insert Table 9. EOSDIS Storage and Computation here]

3.2.4. Conducting Interdisciplinary Investigations

Many of the important scientific questions to be studied by EOS require analyses by interdisciplinary teams using data and information from different combinations of the EOS instruments and *in situ* observations. Twenty-nine investigations have been selected out of several hundred submissions from scientists around the world who responded to the EOS Announcement of Opportunity. The interdisciplinary studies bring together highly talented teams of experts from diverse fields to tackle specific areas of uncertainty regarding the functioning of the Earth as a coupled system. Three examples follow to illustrate how these studies cross traditional boundaries. For additional details on all Interdisciplinary Science Investigations, see the "1993 EOS Reference Handbook" (Asrar and Dokken, 1993).

One study—*Global Water Cycle: Extension Across the Earth Sciences*—will bring together 18 researchers under the leadership of Eric J. Barron of the Pennsylvania State University to study the global water cycle. The goal will be to determine the scope of the water cycle's interactions with all Earth components, and to understand how it affects change on global and regional scales. This study will involve the conversion of patterns observed from space into knowledge of the processes that, linked together, determine the cycling of water in the Earth system. The research strategy involves developing simulation models that assimilate EOS and *in situ* observations to produce information on physical and biological variables and processes rates.

The models will be tested with field studies for calibration and verification, and will provide methods for resolving the presently unknown sources, sinks, and flux rates of the global water cycle. The knowledge gained will then be used to document significant aspects of the water cycle and to develop the needed understanding of past variations to help predict future changes.

Another study—*Interannual Variability of the Global Carbon, Energy, and Hydrologic Cycles*, directed by James E. Hansen of the NASA Goddard Institute for Space Studies—will use pre-EOS and EOS data sets to investigate the interannual variability of key global parameters and processes in the global carbon cycle, the global thermal energy cycle, and the global hydrologic

Spacecraft	Storage (GB/day)	Computation (MFLOPS)
EOS-AM1	673	218
EOS-PM1	376	250
EOS-AERO1	4	21
EOS-ALT1	12	31
EOS-CHEM1	21	151
EOS-COLOR	2	40
TRMM (CERES & LIS)	3	13

Table 9

36a

cycle. The science team will develop, analyze, and make available to other Earth science investigators global geophysical data sets derived from pre-EOS and EOS observations. Developing data sets will involve use of observations in combination with global models that are already developed or currently under development. The analysis will involve studies of several specific interdisciplinary problems—each focused on interactions among components of the Earth system, such as land-atmosphere, ocean-atmosphere, and coupled chemistry-dynamic atmosphere models. Expected near-term results include knowledge of certain Earth system processes that can be investigated using large-scale interannual variability of observed parameters, a mini-EOS-type collection of data sets available in convenient form to other investigators, and improved definition of global measurement and data set needs for EOS.

The third study—*Interdisciplinary Investigation of Clouds and Earth's Radiant Energy System,* led by Bruce A. Wielicki of Langley Research Center—will contribute to understanding the effect of clouds on climate by creating a consistent database of accurately known fields of radiation and cloud properties. Radiative data will be provided as fluxes at the top of Earth's atmosphere, at the Earth's surface, and as flux divergences within the atmosphere. Cloud properties will be provided as measured areal coverage, cloud altitude, shortwave and longwave optical depths, cloud particle size, and condensed water density. The large systematic diurnal variations of radiation and clouds will be resolved by analyzing data from three spacecraft: EOS-AM1 and -PM1 polar platforms and from the low-inclination TRMM satellite.

The combination of these data with global climate models will allow researchers to determine the interaction of clouds with the Earth's climate—a critical issue for understanding global change. Pre-launch studies of radiative transfer models and data analysis algorithms will use existing satellite data along with field measurements of clouds and radiation collected during the First ISCCP Regional Experiment (FIRE).

The 29 EOS Interdisciplinary Science Investigations will exploit the talents and skills of several hundred scientists, and the results and knowledge gained will be made available to other scientists via EOSDIS. Taken together, these studies will promote a comprehensive approach to the study of the Earth as a system.

3.3. SUMMARY

Clearly, implementation of EOS will be a complex undertaking. Yet, the entire process is held together by a simple goal—understanding how the Earth functions as a system, with a definite focus on global climate change. Chapters 1 through 3 have provided an overview of how the design and

implementation of EOS will answer priority science and policy questions. In the following chapters, the process will be considered in greater detail, looking at each priority research area in turn.

4.0. CLOUDS, RADIATION, WATER VAPOR, AND PRECIPITATION

The range of surface temperatures and pressures on Earth is such that water is plentiful in its life-supporting liquid state and yet moves freely and vigorously to its vapor and solid states as well. The more we learn about our desiccated, and apparently barren, neighboring planets, the more we wonder if our good fortune is not a result as well as the cause of life on the Earth.

Opportunities in the Hydrologic Sciences, 1991

4.1. CURRENT UNDERSTANDING

The highest priority science and policy issues confronting EOS are those concerning potential changes in the Earth's water and energy cycles. The climate research community now agrees that the Earth's climate will undergo changes in response to the radiative forcing induced by the increase in trace gases, such as CO_2, CH_4, NO_2, and CFCs.

These changes may profoundly affect atmospheric temperature, humidity, circulation, cloud cover distribution, and especially precipitation patterns. Such changes are likely, in turn, to have significant societal impact. Water is central to the functioning of human society in ways that only become apparent when it is absent or inadequate. In the U.S. alone, half of the $100 billion agricultural industry depends on irrigation, while 90 percent of U.S. electricity generation involves water in some form. Climate models already predict an increased future tendency toward aridity and drought, particularly in the interiors of mid-latitude continents.

The full impact of greenhouse gas forcing depends on feedbacks between atmospheric changes and radiative forcing terms that are inadequately understood. For example, increased atmospheric humidity caused by greater evaporation at the Earth's surface is a near certainty in a warmer climate. At present, we are uncertain about the resulting vertical redistribution of the evaporation, which is essential to understanding the magnitude of water vapor feedback.

The monitoring of clouds, water vapor, and the radiation budget of the Earth has therefore emerged as a key component of a space-based climate monitoring system. The Earth's radiation budget is especially important because it serves as both a tracer of climate change and a forcing function. Understanding the deposition of radiation energy within the climate system is essential, because the solar and longwave fluxes at the top of the atmosphere and the Earth's surface are primary components of the Earth's radiation budget.

Since the general circulation of the atmosphere and oceans is driven by the spatial variation of the net radiative heating, changes in this heating will cause changes in the circulation patterns as well. This will alter the hydrologic cycle, and the distribution of precipitation over the surface of the Earth is likely to be realigned. Changes in oceanic circulation will result in different distributions of sea surface temperature, leading to further atmospheric circulation shifts. There are two areas of central concern about atmospheric elements of the hydrologic cycle: Clouds and atmospheric circulation.

4.1.1. Clouds

The role of clouds proves central in understanding the Earth's radiation balance. Clouds have a strong influence on the radiative energy exchange between the atmosphere and its upper and lower boundaries. They constitute the most important variable in determining the amount of solar energy absorbed by the climate system as well as the amount of infrared energy radiated to space. The effect of cloud cover on solar radiation depends primarily on the optical thickness of the cloud, but it also depends on particle size and phase. The longwave effect depends primarily on cloud-top temperature, which is a function primarily of cloud height.

Effects of solar radiation and thermal emission move in opposite directions. Each is large, but the combined effect is small, depending on many parameters. The balance—where the net result is the difference between two large quantities—has led to a debate on whether clouds play an important feedback role in climate.

While clouds appear to control the energetics of the climate system, the cloud parameters themselves depend on the climate. The radiative effect of clouds on climate is understood in principle, with gaps in present knowledge confined to recognized problem areas. However, the dependence of cloud cover parameters on the variables of the climate system is only understood in isolated areas under limited conditions. As such, cloud process studies need to be performed at two levels: Cloud scale and regional scale.

4.1.2. Atmospheric Circulation

Atmospheric circulation acts as the conveyor of moisture when water vapor evaporates from the ocean and land surfaces, then is transported to other parts of the atmosphere where condensation occurs, clouds form, and precipitation ensues. There is a net outflow of atmospheric moisture from the tropics (where sea surface temperatures are high and the warm atmosphere can hold large amounts of water vapor) to the higher latitudes

(where the moisture is removed through condensation and precipitation processes). A warmer climate will affect the hydrologic cycle, but these prospective circulation changes are not well understood and have been poorly modeled.

Water vapor strongly depends on the temperature, which determines the total amount of water that the atmosphere can hold without saturation. Hence, water vapor amounts decrease strongly from equator to pole and with increasing altitude. Superimposed on this general behavior are smaller variations of water vapor amounts that determine the formation and properties of clouds and rainfall. Generally, water amounts are slightly less over the continents than over the oceans, and the upper atmosphere tends to be drier than the near-surface atmosphere. Researchers do not yet understand all the processes that transport water accurately enough to predict how variations in water will change with temperature.

Most of the processes discussed so far relate to atmospheric dynamics; however, the oceans are equally central in understanding the global energy and hydrologic cycles. The role of the world's oceans in climate change is discussed in greater detail in Chapter 5. Ocean circulation's role in the hydrologic cycle is the result of interactions between the oceans and the atmosphere, but it is not yet clear how this coupled system is balanced. The scales of motion and the energy in both systems are large enough to ensure that the flows are turbulent and non-linear, which limits the ability to make accurate predictions.

To complete this survey of current understanding about hydrology and energy systems, the land component must also be examined (discussed in greater detail in Chapter 7). Here, the critical issue revolves around the interaction of the Earth's surface and the atmosphere. Much more needs to be known about how energy and water fluxes are linked with the state of land vegetation. Many of the uncertainties reflect the lack of coeval measurements of soils, soil moisture, vegetation morphology and physiology, snow depth, and the state of the overlying atmosphere. Direct measurements of evaporation and transpiration are available only at local sites, so that regional and global evaluation of this critical flux is inadequate. The interactions of the land surface and atmosphere are incorporated in only a primitive fashion in global climate models.

4.2. KEY QUESTIONS

The key questions regarding water and energy cycles focus on clouds, greenhouse gases, evaporation, and land surface hydrology:

1) How will clouds, through their influence on the Earth's radiation budget, modulate or enhance tropospheric warming caused by increasing concentrations of greenhouse gases, especially water vapor?
2) How will tropospheric warming from increasing concentrations of greenhouse gases affect atmospheric circulation patterns, therefore regional precipitation patterns?
3) How will the global and regional water balance of precipitation, evaporation/transpiration, and runoff be affected by increasing concentrations of atmospheric trace gases?
4) What are the feedbacks and interactions between the atmosphere and land surface hydrology that will define the response to accelerated human-induced changes in land surface characteristics?

4.3. SCIENCE STRATEGY

During the 1990s, experiments such as the International Satellite Cloud Climatology Project (ISCCP), First ISCCP Regional Experiment (FIRE), Atmospheric Radiation Measurement (ARM), and Earth Radiation Budget Experiment (ERBE) will improve knowledge of cloud behavior, while the Global Water and Energy Experiment (GEWEX) will address large-scale hydrologic issues.

The Tropical Rainfall Measurement Mission (TRMM), to be launched in 1997, will mark the beginning of improved measurements of precipitation over regions where current data are inadequate. The TRMM mission, combined with EOS instruments, will acquire crucial information on surface fluxes of water and the transport of water vapor through the atmosphere. Understanding the role of aerosols in moderating greenhouse forcing will be improved by the French POLDER instrument on ADEOS.

The most important EOS instruments to be deployed in gathering information on water and energy cycles are CERES, MODIS, AIRS/AMSU/MHS, MIMR, and MISR. MODIS, MISR, SAGE III, and EOSP will provide more extensive information on aerosol formation, distribution, and diurnal variability. The combination of CERES and MODIS will allow greatly improved quantification of the large-scale and low frequency variability of net incoming solar radiation and net outgoing longwave radiation and their connection to cloud structure and coverage.

In tandem with SAGE III and EOSP, MISR and MODIS will explore the role of aerosols in radiation balance. Understanding cloud formation processes and radiation interaction will be advanced primarily by the AIRS/AMSU/MHS instruments. In addition, MODIS and MIMR sensors together will provide global mapping of snow cover in all weather conditions.

Several Interdisciplinary Science Investigations focus on global hydrological issues, including:

- *Global Water Cycle: Extension Across the Earth Sciences*, Eric J. Barron
- *Interannual Variability of the Global Carbon, Energy, and Hydrologic Cycles*, James E. Hansen
- *The Hydrologic Cycle and Climatic Processes in Arid and Semi-Arid Lands*, Yann H. Kerr and Soroosh Sorooshian
- *Global Hydrologic Processes and Climate*, William K.M. Lau
- *An Interdisciplinary Investigation of Clouds and the Earth's Radiant Energy System: Analysis*, Bruce A. Wielicki.

4.4. EXPECTED RESULTS

There are many potential gains in knowledge from EOS about hydrologic and energy systems. The following is a list of some important likely results from pre-EOS and EOS-era measurements and improved modeling capabilities:

1) **Define what types of clouds are most important in determining the radiative energy balance of the Earth**—It should also be possible to establish the observed relationship between cloud type descriptions based on satellite data and the top-of-the-atmosphere radiation balance. This will provide insight into what types of clouds are most important for the radiation balance. The understanding gained will help discriminate the mechanisms by which particular types of clouds are generated. Assessing the capabilities of global circulation models to generate similar cloud properties, scientists can then determine how these generating mechanisms might change if the climate warms.
2) **Quantify the observed relationships among local changes in abundance of particular cloud types, atmospheric water vapor distribution, sea surface temperature, and large-scale circulation of the atmosphere**—The greenhouse effect produced by water vapor is linked with cloud radiative forcing, since clouds also moisten their environment.
3) **Determine the physical and optical fine structure of clouds on spatial scales of 1 to 10 km related to their genesis and decay mechanisms and to the large-scale environment**—Researchers will be able to evaluate how much can be learned about the genesis mechanism of clouds and their effect on the environment by increasing the spatial and spectral information available from Earth-orbserving satellites.
4) **Determine the overall role of clouds in controlling the Earth's radiative balance, thus climate**—EOS will determine cloud properties simultaneously with radiative fluxes at the top of the atmosphere, at the surface of the Earth, and within the atmospheric column.

5) **Determine the climate feedbacks between the ocean, land, biosphere, cryosphere, and atmosphere**—EOS data on clouds and radiation will be combined with global circulation models to determine climate feedback mechanisms.
6) **Determine the radiative energy exchange between the surface and the atmosphere**—EOS measurements of radiative fluxes will permit evaluation of the energy flows between the surface, atmosphere, and outer space.
7) **Determine the total poleward energy transport of the Earth-atmosphere system, and of the oceans**—This redistribution of energy drives the large-scale circulation systems of the planet.
8) **Characterize continental-scale water and energy exchanges**—Land-based, airborne, TRMM, and EOS sensors of water and energy budget variables will be used to characterize water and energy exchange processes, leading to improved parameterization of these exchanges in global circulation models.
9) **Develop continental and regional surface hydrologic models with explicit treatment of precipitation, runoff, and snow/ice dynamics over land areas**—This will be verified with remotely sensed data from EOS platforms and from *in situ* measurements.
10) **Develop high-resolution, comprehensive Earth system models that incorporate atmosphere-ocean interaction along with realistic treatments of clouds and the hydrologic cycle**—This will be used with EOS and other data to assess current climate and to predict future climate trends and variations.

5.0. OCEANS: CIRCULATION, PRODUCTIVITY, AND AIR-SEA EXCHANGE

Accurate representation of the ocean in climate models...is critical to developing the ability to predict climate change.

Our Changing Planet: The FY 1993 Research Plan, 1992

5.1. CURRENT UNDERSTANDING

The oceans transport significant quantities of energy and drive long-term changes in climate. Fluxes of energy, momentum, and freshwater between the atmosphere and the ocean surface affect circulation and the availability of both water vapor and energy to the atmosphere. The exchange of CO_2 across the air-sea interface depends on the difference of partial pressure and wind stress at the sea surface.

The world ocean is also the great reservoir of the Earth's water supply, with fully 98 percent of the available water supply stored in the oceans and in sea ice. About 78 percent of global precipitation and 86 percent of evaporation occurs over the oceans [WCRP/GEWEX, 1988; Baumgartner and Reichel, 1975]. The small difference of about 10 percent between the net excess evaporation over precipitation in the oceans is transported by the winds to supply essential precipitation to the continents.

The oceans also serve as huge reservoirs of elements and chemical species to which the climate system is sensitive. In particular, the 600 gigatons of carbon present in the oceanic dissolved organic matter (DOM) pool is equal to the total vegetative carbon reservoir on land. Oceanic DOM has a biogenic origin, but details of its cycle are not well known. Clearly, formation and destruction of DOM depend on the species, hence the environmental oceanic processes that modify the composition of species assemblages will change the quantity of oceanic DOM.

Transfer of carbon and many other chemical species across the air-sea interface is tightly controlled by ocean surface and atmospheric surface layer phenomena, especially winds. The incorporation of inorganic carbon by marine plants and its role in carbon cycling in the ocean is important, but not well understood on mesoscales and seasonal time scales.

Researchers do know that oceanic processes control climate change on many levels. For example, western boundary currents such as the Gulf Stream flow poleward, balancing the global heat and momentum budgets. Oceanic carbon uptake has been seen as a possible mechanism to delay the greenhouse effect.

In general, the global system of ocean currents has been compared to a giant conveyor belt—transporting heat, salt, and chemicals around the planet.

In order to better understand the role of the oceans in global change, scientists need data about the physics of the upper ocean, the biological processes that occur in the upper ocean influencing the chemical form of climate-sensitive species, and the air-sea interaction processes that couple the atmosphere and oceans (i.e., the Earth's two great fluid systems).

5.2. KEY QUESTIONS

1) What are the storage and transport times of heat and greenhouse gases in the ocean?
2) What is the balance between CO_2 ventilation to the atmosphere in newly upwelled water and the rate of formation of organic carbon globally?
3) What is the concentration of pre-formed nutrients in source regions of deep water formation?
4) What is the rate of ocean primary production and new production?
5) How does ecosystem structure control the rate of organic matter transport to deep oceans?
6) Are nutrient-rich oceans limited by atmospheric transport of terrestrially derived dust rich in trace nutrients?
7) What is the rate of production of dimethyl sulfide by phytoplankton?

5.3. SCIENCE STRATEGY

The Sea-Viewing Wide Field Sensor (SeaWiFS) will begin to provide ocean color measurements in 1994, from which biomass and biological productivity can be estimated. Since 1992, the Ocean Topography Experiment (TOPEX)/Poseidon has provided measurements of ocean topography to improve knowledge of the circulation of the upper ocean. The NASA Scatterometer (NSCAT) will fly on the Japanese Advance Earth Observing System (ADEOS) mission in 1995, to measure wind stress at the ocean surface, while also providing surface wind information for inclusion in models of the Earth's climate.

Continuing observations of integrated atmospheric liquid water, water vapor, and surface wind speed by the Department of Defense (DoD) Special Sensor Microwave/Imager (SSM/I) are being used to make estimates of monthly mean air-sea fluxes of heat and water. In addition, SSM/I observations of sea ice—along with synthetic aperture radars on the European Remote-Sensing Satellite-1 (ERS-1), Japan's Earth Resources Satellite-1 (JERS-1), and

Radarsat—will be used in models of bottom-water formation and heat flux in the high-latitude oceans.

NOAA's Advanced Very High-Resolution Radiometer (AVHRR) will provide high-resolution sea surface temperature in cloud-free regions. Coupled with global field programs such as the World Ocean Circulation Experiment/Tropical Ocean Global Atmosphere (WOCE/TOGA) and Joint Global Ocean Flux Study (JGOFS), significant advances will be made during this period in understanding the role of the ocean in the Earth system.

In 1998 and beyond, MODIS sensors flying as part of the EOS Program will continue the SeaWiFS measurements of ocean color and improve the accuracy and resolution of sea surface temperature measurements. Subsequently, more complete spectral measurements—by sensors such as the Global Imager (GLI) flying on ADEOS—will allow separation of phytoplankton pigment into its critical components, thus significantly improving understanding of ocean biogeochemical cycles.

NSCAT II on the ADEOS IIa mission will continue the essential data set for ocean vector winds, allowing improved estimation of critical air-sea heat, momentum, and chemical fluxes.

AIRS/AMSU/MHS will provide accurate sea surface temperatures, as well as boundary layer temperature and moisture needed for monitoring air-sea energy exchange. MIMR will provide information about sea ice and atmospheric water content at a higher spatial resolution than SSM/I, and the added 6 GHz channel will allow all-weather estimation of sea surface temperature under cloud cover. Continuous time series of TOPEX/Poseidon-class altimetric measurements will allow the study of critical components of low frequency variability of basin-scale ocean circulation. The EOS-ALT series will continue ocean topography measurements started by TOPEX/Poseidon.

Several Interdisciplinary Science Investigations are directly related to better understanding of the oceans, including:

- *Coupled Atmosphere-Ocean Processes and Primary Production in the Southern Ocean,* Mark Abbott
- *Biogeochemical Fluxes at the Ocean/Atmosphere Interface,* Peter G. Brewer
- *Interdisciplinary Studies of the Relationships between Climate, Ocean Circulation, Biological Processes, and Renewable Marine Resources,* Graham P. Harris
- *Climate Processes Over the Oceans,* Dennis L. Hartmann
- *The Role of Air-Sea Exchanges and Ocean Circulation in Climate Variability,* W. Timothy Liu

- *Investigation of the Atmosphere-Ocean-Land System Related to Climatic Processes,* Masato Murakami
- *Polar Exchange at the Sea Surface (POLES): The Interaction of Oceans, Ice, and Atmosphere,* Drew Rothrock
- *Middle and High Latitudes Oceanic Variability Study,* Meric A. Srokosz.

5.4. EXPECTED RESULTS

There will be many advances over present knowledge of the oceans from both the pre-EOS and EOS-era missions. The following is a partial list of some of the potential advances expected:

1) **Significant improvements in the quality, coverage, and availability of ocean data sets on a global basis**—The pre-EOS era will witness advances in single oceanographic disciplines (e.g., biology, chemistry, and physics), while the EOS era will focus on the interaction of these systems. The interfaces are complex, and many of the interactions are non-linear; however, progress in understanding the processes controlling these linkages is anticipated.
2) **Significant improvement in models**—Toward the end of the 1990s, coupled atmosphere-ocean models capable of assimilating complex data fields will be developed. In the EOS era, predictive models will become operational through a combination of experience in working with these earlier models, the continued evolution in understanding of the relevant processes, and the beginning of a consistent time series of observational data accessible via the EOS Data and Information System (EOSDIS). The models in the EOS era will contain more processes explicitly, and the parameterizations that remain will be better understood. Continued effort will be placed on developing fully predictive models of ocean biogeochemistry.
3) **Major improvements in coupled atmosphere-ocean models**—Because the links between these two systems are so poorly understood, this may well be the most important development in advancing global change research.
4) **Determine in detail the accuracy of scatterometer wind measurements as a function of both winds and other geophysical phenomena**—This task is critical, since eventual use of remotely sensed data to force and test advanced models requires quantitative estimates of data accuracy to allow proper assimilation and to ensure proper interpretation of results.
5) **Develop and test techniques for extrapolating and interpolating scatterometer data to regular space-time grids and establish the quantitative accuracies of the products**—Using TOPEX/Poseidon data, researchers expect to generate several basin-scale and regional ocean

wind gridded products for the Atlantic, North Pacific, Tropical Oceans, and Southern Ocean.

6) **Apply scatterometer data in several ocean air-sea and biophysical interaction models**—Key areas of near-term study will include large-scale tropical air-sea interaction modeling, the Southern Ocean, and biophysical modeling of the Gulf Stream region of the Atlantic.
7) **Improve techniques for calculating latent and sensible heat, momentum, and moisture, as well as greenhouse gases over the global oceans**—May need a touch of explanation here....
8) **Develop advanced techniques for the assimilation of scatterometer winds into GCMs**—This development will have special relevance to improving medium-range weather forecasting.
9) **Improve understanding of the wind-driven response of ocean circulation**—It is especially important to analyze how this process controls the distribution of heat storage in the upper ocean.

6.0. GREENHOUSE GASES

Minor species, such as O_3 and the hydroxyl radical (OH) have a major influence on the chemistry of the atmosphere and in this capacity have become directly important to human societies.

Earth System Science: A Closer View, 1988

6.1. CURRENT UNDERSTANDING

Human activities are changing the concentrations of trace constituents in the atmosphere, and both chemical and dynamic responses of the atmosphere to this forcing are occurring. Ozone (O_3) is the element of greatest interest, because of its importance in preventing ultraviolet radiation from reaching the Earth's surface and its contribution to global warming as a greenhouse gas.

In the stratosphere, large springtime ozone depletions in the Antarctic have been shown to be related to anthropogenic chlorine- and bromine-containing compounds. In addition, recent research efforts have detected mid- and high-latitude ozone decreases in the northern hemisphere that exceed changes predicted by standard models. By contrast, there have been increases in background ozone in the troposphere, especially in the northern hemisphere.

Changes in tropospheric ozone may be accompanied by changes in the oxidizing capacity of the troposphere (i.e., its ability to react with a variety of compounds). This in turn would affect the amounts of those compounds reaching the stratosphere. The major gap in our current knowledge about the troposphere is that we do not know whether tropospheric O_3 is increasing, and this is an important question for EOS to answer. The abundance of OH controls the lifetime of chlorofluorocarbon (CFC) substitutes. If OH increases, fewer HCFCs will reach the stratosphere; however, if it decreases, the opposite will hold true.

6.2. KEY QUESTIONS

Four scientific issues form the focus for investigation of tropospheric chemistry. Besides trace gases in the atmosphere and their role in chemical and radiative processes, tropospheric chemistry questions are closely related to issues in other priority domains:

1) **Trace gases and climate (global warming)**
   - What is the source distribution of radiatively active gases with natural and anthropogenic origins (CH_4, N_2O, CO_2)?

- What is the natural and anthropogenically induced variability in ecosystems caused by changes in temperature, acid deposition, rainfall, and ultraviolet radiation?

2) **Tropospheric ozone and global pollution**
   - What is the natural variability in tropospheric ozone?
   - Is tropospheric O_3 increasing? Are its precursors (CO, NO_x, and hydrocarbons) increasing?
   - What are the roles of convection, stratosphere-troposphere exchange, and long-range transport in O_3 formation?
   - What are the magnitudes of ozone production from industrial activity and biomass burning?
   - What is the effect of O_3 changes on forests, agriculture, and ecosystems?
3) **Oxidizing capacity of the atmosphere**
   - What are the spatial distributions of OH andH_2O_2 in the troposphere?
   - What is the total OH abundance?
   - Does the OH abundance change during the EOS observing period?
4) **Budgets and sources of trace gases that contain carbon, sulfur, and nitrogen**
   - What are the terrestrial and oceanic contributions to the global carbon cycle?
   - What is the anthropogenic contribution to these trace gases and how is it distributed?
   - Are there trends in the emissions of radiatively and photo-active gases, both natural and anthropogenic?

- Is there large-scale interaction of clouds and precipitation with trace gases?

6.3. SCIENCE STRATEGY

The variables needed to answer the main questions related to the troposphere involve measuring from space tropospheric trace gases with an intermediate lifetime of days to months. Researchers have to infer the concentration of short-lived trace gases from ultraviolet flux and measurement of the intermediate lifetime gases, using an appropriate model, coupled with data assimilation. Results are then validated by field campaigns. In addition to trace gases, information from other disciplines such as ocean color, biomass burning, and land vegetation are needed.

Before the EOS launches begin, field campaigns and existing satellite data will help find new information about the relationships between various tropospheric gases and source gases. The stratospheric instruments—such as the Total Ozone Mapping Spectrometer (TOMS) and those onboard the Upper Atmosphere Research Satellite (UARS)—will help scientists learn about

stratospheric/tropospheric exchange of trace gases. SAGE/TOMS O_3 differential will help to approximate tropospheric residual ozone, providing information on regional and seasonal mid-troposphere ozone behavior.

Surface fluxes of some land- and ocean-derived trace gases will be estimated using Advanced Very High-Resolution Radiometer (AVHRR), Sea-Viewing Wide Field Sensor (SeaWiFS), and four-dimensional assimilation techniques. On the international side, the Japanese Interferometric Monitor for Greenhouse Gases (IMG) instrument will supply global measurements of long-lived trace gases in the pre-EOS era.

Less will be learned about the chemistry of the lower stratosphere from UARS, but aircraft campaigns during the next decade will add greatly to knowledge of lower stratospheric and tropospheric chemistry. These campaigns will focus on specific trace gas transport and transformation mechanisms, but will not provide global surveys of tropospheric constituents such as ozone, ozone precursors, and other biogeochemically important trace gases.

In the EOS era, TES and MOPITT will investigate the interaction and evolution of tropospheric trace and greenhouse gases with the climate and biosphere. The combination of measurements provided by SAGE III, HIRDLS, and MLS will provide additional data on stratospheric ozone, water vapor, and temperature. These instruments will help address questions of stratospheric-tropospheric exchange, changes in upper tropospheric ozone and water vapor (key greenhouse gases), and changes in the chemistry of the lower stratosphere, including the role of heterogeneous processes.

EOS Interdisciplinary Science Investigations focused on the chemistry of the troposphere and lower stratosphere include the following:

- *Biogeochemical Fluxes at the Ocean/Atmosphere Interface*, Peter G. Brewer
- *Observational and Modeling Studies of Radiative, Chemical, and Dynamical Interactions in the Earth's Atmosphere*, William Grose
- *Interannual Variability of the Global Carbon, Energy, and Hydrologic Cycles*, James E. Hansen
- *The Role of Air-Sea Exchanges and Ocean Circulation in Climate Variability*, W. Timothy Liu
- *Changes in Biogeochemical Cycles*, Berrien Moore III
- *A Global Assessment of Active Volcanism, Volcanic Hazards, and Volcanic Inputs to the Atmosphere from EOS*, Peter J. Mouginis-Mark
- *Using Multi-Sensor Data to Model Factors Limiting Carbon Balance in Global Grasslands*, David S. Schimel

- *Investigation of the Chemical and Dynamical Changes in the Stratosphere Up to and During the EOS Observing Period,* Mark R. Schoeberl
- *Biosphere-Atmosphere Interactions,* Piers Sellers.

6.4. EXPECTED RESULTS

The following are some of the improvements in knowledge that can be expected about the chemistry of the troposphere and lower stratosphere:

1) Better understanding of continued trends in tropospheric ozone at the surface and at locations of ozonesonde release
2) Better understanding of the trace constituent distributions in the upper troposphere
3) Better understanding of the natural and anthropogenic input of trace constituents into the troposphere
4) Improvements in global tropospheric chemical modeling
5) Better understanding of the temperature, dynamics, and stratospheric-tropospheric exchange in the tropopause region
6) Improved understanding of the trace constituent distributions in the upper troposphere, especially for carbon monoxide and ozone
7) Availability of information needed for improving models of tropospheric chemistry (especially true for the distribution of global ozone and the hydroxyl radical)
8) Wind measurements in the stratosphere and high-resolution trace constituent measurements in the upper troposphere and stratosphere (improved studies of trace constituent budgets and stratosphere-troposphere exchange)
9) Dramatically improved understanding of the relationship between temperature, trace constituent concentrations, and formation of polar stratospheric clouds in the high-latitude lower stratosphere
10) Better understanding of the transport mechanisms between the troposphere and stratosphere.

7.0. LAND SURFACE: ECOSYSTEMS AND HYDROLOGY

Ultimately...shifts in the functions of terrestrial ecosystems induce changes in the climate of the globe and the chemistry of the atmosphere and oceans.

From Pattern to Process: The Strategy of the Earth Observing System, 1987

7.1. CURRENT UNDERSTANDING

There have been few attempts to link physical climate and the terrestrial biosphere, realistically describing the interactions between the surface and the atmosphere. However, the vegetated land surface includes many systems that regulate the flux of moisture from the soil to the atmosphere and also the uptake and release of CO_2. The state of the vegetation and the water-holding properties of the soil column determine how these controls operate.

Many of the uncertainties reflect the lack of coeval measurements of soils, soil moisture, vegetation morphology and physiology, snow depth, and the state of the overlying atmosphere. The interactions of the land surface and the atmosphere are incorporated only in a primitive fashion in global climate models, through highly simplified boundary layer processes. Improved estimates of water and energy fluxes between the atmosphere and the land surface, and of runoff over the land surface and into oceans, are needed to determine the exchange of moisture and energy between the land surface and the atmosphere. This information is required for realistic climate simulations. In addition, we need to know more about terrestrial processes, because regional precipitation is controlled (in part) by them.

Terrestrial ecosystems play significant roles as both sources and sinks for greenhouse gases, and photosynthesis is the primary means of transforming and removing carbon dioxide from the atmosphere. Terrestrial vegetation responds to increasing concentrations of atmospheric carbon dioxide through increased photosynthetic carbon fixation, which could result in increased carbon storage in vegetation and soils. Yet, increasing temperatures, which may accompany the increasing carbon dioxide concentrations, will cause increased rates of respiration and decomposition within ecosystems. Thus, a net ecosystem response to carbon dioxide is difficult to assess.

At present, researchers are not able to balance the global carbon budget. We know that about half of the anthropogenically produced carbon released annually does not remain in the atmosphere. Known terrestrial and oceanic sinks do not account for all "missing" carbon. Changes in land use and management (especially deforestation and biomass burning) reduce the standing stock of the terrestrial biosphere and cause the direct release of carbon dioxide into the atmosphere. The total contribution of deforestation

and biomass burning to atmospheric concentrations of carbon dioxide is not well known, and knowledge of the link between these activities and other greenhouse gases is equally uncertain.

We also know that atmospheric methane concentrations are increasing at a rate of 0.9 percent annually, but do not know the cause. Several proposed anthropogenic sources for increasing methane concentrations in the atmosphere involve the terrestrial biosphere. These include rice cultivation, ruminant rearing, and biomass burning. In addition, natural wetlands serve as a significant source of methane under anaerobic conditions, and regional change caused by climate warming or increased duration of flooding could lead to large increases in their emissions. Climatic warming and drying of wetlands, on the other hand, could reduce their methane emissions. In areas where the storage of organic carbon in soils is high, this could lead to increased decomposition and emission of carbon dioxide. Scientists now have a reasonably good understanding of how these processes work in some localized areas at particular times of year, but do not understand them on a global scale or over long time periods.

Terrestrial ecosystems will change over time in response to changes in their biogeochemical environment. Changes in atmospheric concentrations of greenhouse gases are likely to lead to shifts in the species composition, structure, and element cycling processes of terrestrial ecosystems. These developments may well result in new ecosystems that respond differently to the greenhouse gas environment. Long-term changes and feedbacks remain unclear.

7.2. KEY QUESTIONS

1) How will the land surface biophysical controls on the carbon, energy, and water cycles respond to and feed back on climate change? Most GCM simulations of climate system responses to increasing atmospheric CO_2 predict that there will be a warming of the continental interiors. This could lead to a decrease in evapotranspiration and amplification of warming and drying.
2) How will the respiration component of the carbon cycle (particularly decomposition) change with climate change?
3) How will ecosystems change in response to climate change and anthropogenic pressure, particularly feedbacks onto the climate system and cycling and storage of carbon and trace constituents? The projected changes in the physical climate system will exert pressures on terrestrial ecosystems, in addition to local changes brought about by human activity and natural processes.
4) How are atmospheric trace gases distributed globally, and how are the concentrations changing over time? This is a question that is relevant

to other priority areas, but is also important here because of the role of CH_4 and CO in relationship to ecosystem processes.

7.3. SCIENCE STRATEGY

In this decade, programs such as the International Satellite Land Surface Climatology Project (ISLSCP) and the Global Energy and Water Cycle Experiment (GEWEX) will examine exchanges of water, energy, and chemicals between the surface and the atmosphere. In addition, the Landsat archive and continuing series will be used to examine historical changes in land cover, land use, and the distribution of biomass.

Until the launch of EOS, the Advanced Very High-Resolution Radiometer (AVHRR) will be the only source of data for global-scale monitoring of vegetation dynamics on phenological and sub-seasonal time scales, which is essential for the study of the exchanges of water, energy, and carbon between the land and the atmosphere.

Synthetic aperture radars (SARs) flying on European, Japanese, and Canadian satellites will also monitor deforestation and surface hydrology. The ability of SAR to penetrate cloud cover and dense plant canopies make it particularly valuable in rainforest studies.

After 1998, the EOS instruments (particularly MODIS and MISR) will support global mapping of the surface vegetation model exchange of trace gases, water, and energy with the atmosphere. ASTER will provide simultaneous multispectral, high-resolution detail to support this mapping. In addition, MISR's ability to correct land surface images for changing atmospheric conditions and sun-sensor geometry will qualitatively increase land biosphere knowledge. MIMR will improve mapping of snow cover and snow water equivalent in all-weather conditions, along with vegetation moisture.

Interdisciplinary Science Investigations directly relevant to land surface hydrology and ecosystems include the following:

- *Long-Term Monitoring of the Amazon Ecosystems through EOS: From Patterns to Processes*, Getulio T. Batista and Jeffrey E. Richie
- *Northern Biosphere Observation and Modeling Experiment*, Josef Cihlar
- *Hydrology, Hydrochemical Modeling, and Remote Sensing in Seasonally Snow-Covered Alpine Drainage Basins*, Jeff Dozier
- *The Hydrologic Cycle and Climatic Processes in Arid and Semi-Arid Lands*, Yann H. Kerr and Soroosh Sorooshian
- *Changes in Biogeochemical Cycles*, Berrien Moore III

- *Using Multi-Sensor Data to Model Factors Limiting Carbon Balance in Global Grasslands,* David S. Schimel
- *Biosphere-Atmosphere Interactions,* Piers Sellers
- *Use of a Cryospheric System (CRYSYS) to Monitor Global Change in Canada,* Réjean Simard.

7.4. EXPECTED RESULTS

The following are some of the expected results from the investigations of land hydrology and ecosystem processes:

1) Operation of four-dimensional models to provide continuous global estimates of air temperature, humidity, wind velocity, radiation fluxes, shear stress, cloudiness, snow cover, and precipitation
2) Global multi-temporal measurements (sub-seasonal to decadal) of terrestrial vegetation dynamics
3) High spatial resolution observations of ecosystem extent and character, allowing a better understanding of land cover changes and community-scale changes associated with anthropogenic influences, climate-forced succession, or disturbance.

8.0. GLACIERS AND POLAR ICE SHEETS

There remains the possibility that, under the influence of global warming, the West Antarctic Ice Sheet might become unstable and surge into the ocean, causing a global rise in sea level....

Earth System Science, A Closer View, 1988

8.1. CURRENT UNDERSTANDING

A central concern about global warming is that melting glaciers and ice sheets will cause the sea level to rise, rendering certain coastal areas uninhabitable. A 1-m change in sea level would translate into major shifts in shoreline, with both economic and legal ramifications. Even 30-cm changes can be important for coastal communities and coastal engineering practices. For all these reasons, sea level rise, resulting from a combination of increased water temperature and melting ice, is one pressing matter put forth by the Intergovernmental Panel on Climate Change (IPCC). Determining whether this is a possibility requires input from the oceanography, climatology, hydrology, and solid Earth science disciplines.

Knowledge of the motions of the Earth along ocean coastlines and near the margins of ice sheets is needed if scientists are going to be able to determine changes in the volumes of ice and water. These measurements require observations from space to establish an absolute vertical reference frame for tide gauge and altimetric measurements, and to monitor deformations of the solid Earth near the margins of the oceans and ice sheets. Ultimately, predictions of sea level change depend directly on estimates of the mass balance of the ice on the Earth's land surfaces. Changes in the mass balance of glaciers and ice sheets are also time-integrated indicators of climate change.

In the pre-EOS period, radar altimeter data from Seasat and Geosat for Antarctica do not exist, and they are available for Greenland only to a latitude of 72°N. Surface measurements of mass balance are sparse, creating an uncertainty in the state of the Earth's second largest reservoir of water.

Current knowledge is inadequate to assess whether the Antarctic and Greenland ice sheets are growing or shrinking. Results from field work show that some glaciers are getting larger, while others are becoming smaller. Extrapolations from these observations to infer the contribution to sea level have been stricken by large errors; thus, the mass balance for the big polar ice sheets is not known, and where reliable estimates of ice thickening/thinning are available, we do not know why the ice is behaving as observed. For all these reasons, we currently cannot predict the response to global warming of the polar glaciers and ice sheets.

Much more also needs to be known about snow-accumulation rates, melting rates, and iceberg calving rates.

8.2. KEY QUESTIONS

1) What is the current mass balance of the polar ice sheets?
2) Are these ice sheets growing or thinning?
3) What are snow accumulation and melting rates?
4) What are the iceberg calving rates?
5) Will changes in ice sheet and glacier mass balance result in a significant rise in sea level in the next century?

8.3. SCIENCE STRATEGY

Prior to the EOS era, ERS-1 and -2, JERS-1, SARs, and Radarsat will provide useful data, but these sensors are only going to be operating for limited periods of time, and with limited coverage. The measurements of sea level and ice volumes require accurate control of satellite orbits, geodetic level measurements of the vertical movements of the land around the oceans and ice sheets, and the establishment of a uniform global reference frame for vertical movements.

EOS instruments that are important to achieving these objectives include SSALT, DORIS, TMR, and GLAS. GLAS, the laser altimeter, is the key instrument for starting mass balance measurements of polar ice sheets, and it will fly on the EOS-ALT series starting in 2002. ASTER, a high-resolution imager flying on the EOS-AM1 platform in 1998, will be a powerful tool for mapping glacier features, providing data from which glacier flow rates can be measured. MODIS—flying on both the EOS-AM and -PM series—will provide the broad patterns of areal extent and coverage that are required. MODIS can locate areas where changes are taking place, and these areas can then be examined by high-resolution instruments to determine more detail.

Several Interdisciplinary Science Investigations are examining the polar regions and issues related to ice sheets, glaciers, and sea level, as follow:

- *Global Water Cycle: Extension Across the Earth Sciences*, Eric J. Barron
- *Hydrology, Hydrochemical Modeling, and Remote Sensing in Seasonally Snow-Covered Alpine Drainage Basins*, Jeff Dozier
- *Climate, Erosion, and Tectonics in the Andes and Other Mountain Systems*, Bryan L. Isacks
- *Use of a Cryospheric System (CRYSYS) to Monitor Global Change in Canada*, Réjean Simard

- *Earth System Dynamics: The Determination and Interpretation of the Global Angular Momentum Budget Using EOS*, Byron D. Tapley.

8.4. EXPECTED RESULTS

There are several major results expected from these research efforts on glaciers and ice sheets, including:

1) Characterization of the annual mean sea level with an uncertainty of a few millimeters
2) Knowledge of the change in mass balance of the major ice sheets
3) Substantial knowledge of the amount, distribution, and spatial/temporal extent of snow
4) The foundation for predicting whether global warming will lead to an increase in sea level.

9.0. OZONE, CLIMATE, AND THE BIOSPHERE

The people of the world are conducting a continuing, inadvertent experiment with the Earth's atmosphere that is altering its properties on a global scale.

UARS: A Program to Study Global Ozone Change, 1991

9.1. CURRENT UNDERSTANDING

The middle and upper stratosphere is the region of ozone formation, and rapid anthropogenic chemical changes are occurring here. Ozone loss is associated with these changes, as is possible cooling of the middle and upper stratosphere. Recent findings of ozone depletions at the poles and even in the mid-latitudes are creating great concern about this area of research. This loss will increase the ultraviolet flux into the lower atmosphere, and more precise knowledge of these processes is increasingly vital.

The basic method of research on this region is to validate current models and hypotheses through long-term global monitoring of key stratospheric species and physical processes. Validation of models takes place through global satellite observations, aircraft and balloon *in situ* observations, and ground-based methods. The minimum requirements for this monitoring consists of a set of species that characterizes the main chemical cycles involving ozone, and measurements of the basic physical environment of the stratosphere.

The minimum chemical set is determined by a radical and a reservoir from each of the major chemical families (O_x, NO_x, ClO_x, HO_x) and the source gases for these families (e.g., N_2O for the NO_x family). The physical environment measurement set includes temperature, wind, ultraviolet flux, and aerosol/cloud amounts.

9.2. KEY QUESTIONS

1) Do we understand the evolution of stratospheric trace gas composition during a period of large anthropogenically forced changes in the stratosphere?
2) Can we understand/predict global ozone changes and the resulting changes in ultraviolet flux?
3) How strongly will chlorine affect the upper stratosphere during the EOS period when chlorine reaches unprecedented levels?
4) How will increasing greenhouse gases and water vapor affect the chemistry and dynamics of the stratosphere?

9.3. SCIENCE STRATEGY

Measurement requirements will differ for different species and physical processes. Continuous global measurement of temperature, winds, aerosols/clouds, long-lived trace gases, and some radical and most reservoir species are required. Long-term, high-precision, continuous monitoring of ozone, temperature, and some reservoir gases are needed for global trends. The Upper Atmosphere Research Satellite (UARS) will generate the most important data on the stratosphere prior to EOS; however, UARS is designed to be operational for only 3 years, and no measurements of the HO_X species will be made.

UARS, along with the NOAA SBUV-2 and the Shuttle ATLAS missions, will continue to examine the chemical and dynamical processes of the middle and upper stratosphere, the mesosphere, and lower thermosphere, including high-altitude solar-atmospheric effects. SAGE II will also provide high-precision ozone, water, and aerosol measurements. The ground-based Network for Detection of Stratospheric Change (NDSC) will complement the spaceborne measurements.

Starting with EOS-CHEM1 in 2002, HIRDLS, MLS, and SAGE III will monitor the middle and upper stratosphere. SAGE III—flying in both polar and inclined orbits—will continue and improve the high-precision ozone, water, and aerosol record begun by SAGE I and II. HIRDLS will provide high spatial resolution daily global mapping of temperature, ozone, water, methane, CFCs, and other important trace gas species. The inclusion of MLS will complete the minimum required trace gas measurement set with observations of hydroxyl and halogen oxide radicals. The EOS measurements will be augmented by a suite of European Space Agency (ESA) stratospheric instruments and the continued expansion of NDSC.

The Interdisciplinary Science Investigations most directly relevant to questions about the stratosphere follow:

- *Observational and Modeling Studies of Radiative, Chemical, and Dynamical Interactions in the Earth's Atmosphere,* William Grose
- *Chemical, Dynamical, and Radiative Interactions through the Middle Atmosphere and Thermosphere,* John A. Pyle
- *The Development and Use of a Four-Dimensional Atmospheric-Ocean-Land Data Assimilation System for EOS,* Richard B. Rood
- *Investigation of the Chemical and Dynamical Changes in the Stratosphere Up to and During the EOS Observing Period,* Mark R. Schoeberl.

9.4. EXPECTED RESULTS

The distribution, causes, and magnitude of changes of stratospheric ozone will be better understood, including improved knowledge of:

1) Continued trends of stratospheric ozone
2) The connection between atmospheric composition, solar inputs, and atmospheric temperature
3) Distribution of trace constituents in the stratosphere and their long-term changes with time
4) Distribution and properties of stratospheric aerosols and polar stratospheric clouds
5) Global stratospheric models
6) Stratospheric data assimilation.

10.0. VOLCANOES AND CLIMATE CHANGE

Since major eruptions...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.

Earth System Science, A Closer View, 1988

10.1. CURRENT UNDERSTANDING

Solid Earth processes are important to climate change, particularly in their interactions with the hydrologic cycle and ecosystems, and more directly through input of particulates and aerosols by volcanic eruptions and wind erosion.

Eruptions of volcanoes, such as Mount Pinatubo in 1991, can inject millions of tons of ash, gases, and aerosols into the upper troposphere and lower stratosphere over a time scale of a week to several months. Assessing the impact of these eruptions on the Earth system requires estimations of the rate at which solid and gaseous material are ejected and measurements of the nature and recovery time of the transient disturbances to the atmosphere, land surface, and/or sea surface.

Particularly in the case of volcanogenic material injected into the stratosphere, it is the rate of conversion of sulfur dioxide to sulphate aerosols and the residence time of the aerosols in the stratosphere that are responsible for the duration of the regional or hemispheric cooling associated with volcanic eruptions. The direct and indirect effects of eruptions on a wide range of biomes, especially alpine or boreal biomes that are already under stress, can last for months or decades.

While explosive eruptions are more spectacular than volcanic activity that produces lava flows and volcanic domes, the contribution of gases released into the atmosphere from surface activity may also have significant impact on the Earth system.

Because of the greater solubility of sulfur in basaltic magmas compared to more silicic magmas, eruptions of volcanoes such as those found in Iceland can inject many times more sulfur into the atmosphere than an eruption of an equivalent volume of silicic magma. The 1783 eruption of Laki in Iceland is a perfect example. Eruption of large volumes of basalt over 7 months resulted in a volcanic fog that affected the weather in northern Europe for at least 2 years.

10.2. KEY QUESTIONS

1) What are the temperatures and morphologies of lavas and plumes?
2) What is the rate at which solid and gaseous materials are erupted?
3) What is the topography of volcanic landforms?
4) What are the inflation/deflation rates of volcanic craters and rift zones?
5) What is the rate of conversion of sulfur dioxide to sulfate aerosols?
6) What is the residence time in the atmosphere of volcanic aerosols that have an effect on climate?

10.3. SCIENCE STRATEGY

The primary instrument package for surface imaging (ASTER, MODIS, and MISR) will contribute to studies of volcanic processes as well as many other solid Earth-related subjects. ASTER, MISR, and EOSP will examine volcanic plumes and aerosols, and SAGE III will give additional information on aerosols reaching the upper troposphere and lower stratosphere.

Volcanoes pose specific requirements to detect and measure the temperatures and morphologies of lavas and plumes. The temporal perspective of the activity produced by the EOS sensors is critical to the analysis of both explosive and lava-producing eruptions. Gas release during an eruption may vary on time scales of a few hours and can be related to the segment of the subsurface magma reservoir that is being tapped at different stages of the eruption.

In lava flow fields, magma production rates, cooling history, and spatial distribution of activity provide important information on the internal structure of the volcano. The high spatial resolution of the EOS sensors is important because of the relatively small size of the phenomena. In addition, the determination of pixel-integrated temperatures requires both high spatial resolution and high spectral resolution. ASTER and Landsat are vital for these temperature determinations. MODIS will detect changes in the areas of the volcanoes, while MISR's ability to determine the amounts of particulates in the atmosphere will also be useful in considering the effect of volcanoes on climate.

SAGE III, TES, and MLS will determine the concentration of SO_2 and rate of dispersal around the globe. Modeling of the dynamics of the eruption plume and rate of release of SO_2, HCl, CO, H_2O, and other gases points to the magnitude of the eruption, magma chemistry, and tectonic setting. Using TES and MLS to monitor the abundance of gas species accompanying an eruption allows for assessment of magma residence time and tectonic setting.

The two Interdisciplinary Science Investigations with greatest relevance to this topic follow:

- *Climate, Erosion, and Tectonics in the Andes and Other Mountain Systems*, Bryan L. Isacks
- A Global Assessment of Active Volcanism, Volcanic Hazards, and Volcanic Inputs to the Atmosphere from EOS, Peter J. Mouginis-Mark.

10.4. EXPECTED RESULTS

1) Greatly improved understanding of temperatures and morphologies of lavas and plumes
2) New information on lava flow fields, magma production rates, cooling history of lava flows, and spatial distribution of volcanic activity
3) Plume-height measurements
4) Measures of topographic change resulting from eruptions
5) Improved understanding of the links between volcanic eruptions and global climate.

11.0. CONCLUSIONS

The most compelling images provided to us by the space program are those looking homeward at Earth floating in the void of space.

From Pattern to Process: The Strategy of the Earth Observing System, 1987

We think of exploration as being a process of humanity leaving planet Earth to go out into the solar system and beyond. However, from the orbiting of the first satellite to the flights of the first human beings into space, there has also been a tendency to look back, to see the Earth from space and understand it in a new way. This process has now led to the Earth Observing System (EOS)—a worldwide enterprise aimed at understanding our home planet with a depth and breadth that could not have been imagined even a few decades ago.

When we consider the number of launch vehicles, instruments, interdisciplinary studies, disciplines, information systems, variables, and unknowns involved in the effort, the strategy behind it may be difficult to comprehend. However, taken as a whole, the vision that inspires the mission is easy to grasp. It is the vision of humanity taking greater responsibility for the Earth system, basing policy decisions about the environment on scientific understanding of global change. It is the vision of humanity being able to predict the effects of its own actions on the natural system, and thereby being able to adapt to new conditions or ameliorate negative impacts whenever possible.

EOS is an opportunity for those interested in space exploration and those interested in preserving the environment to come together in a common cause, using the view of the Earth from space to protect the planet and all the living systems on it. As we approach the beginning of a new century and a new millennium, EOS offers us the opportunity to become stewards of the planet and its resources.

ACRONYMS

AATSR	Advanced Along-Track Scanning Radiometer
ACRIM	Active Cavity Radiometer Irradiance Monitor
ADALT	Advanced Radar Altimeter
ADC	Affiliated Data Center
ADEOS	Advanced Earth Observing System
AIRS	Atmospheric Infrared Sounder
ALT	Altimeter
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AO	Announcement of Opportunity
ARGOS+	Argos Data Collection and Position Location System
ARM	Atmospheric Radiation Measurement
ASAR	Advanced Synthetic Aperture Radar
ASF	Alaska SAR Facility
ASCAT	Advanced Scatterometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATLAS	Atmospheric Laboratory for Applications and Science
ATLID	Atmospheric Lidar
AURIO	Auroral Imaging Observatory
AVHRR	Advanced Very High-Resolution Radiometer
AVNIR	Advanced Visible and Near-Infrared Radiometer
CEES	Committee on Earth and Environmental Sciences
CERES	Clouds and Earth's Radiant Energy System
CFC	Chlorofluorocarbon
CIESIN	Consortium for International Earth Science Information Network
CNES	Centre National d'Etudes Spatiales
CRYSYS	Cryospheric System
CZCS	Coastal Zone Color Scanner
DAAC	Distributed Active Archive Center
DADS	Data Archive and Distribution System
DOM	Dissolved Organic Matter
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
(D)PR	(Double) Precipitation Radar
DRSS	Data Relay Satellite System
EAJ	Environment Agency of Japan
EDC	EROS Data Center
EDOS	EOS Data and Operations System
E-LIDAR	Experimental Lidar
ENVISAT	Environmental Satellite
EOC	EOS Operations Center
EOS	Earth Observing System

EOS-COLOR	EOS Ocean Color Instrument
EOSDIS	EOS Data and Information System
EOSP	Earth Observing Scanning Polarimeter
EP	Earth Probe
EPA	Environmental Protection Agency
ERBS	Earth Radiaton Budget Satellite
EROS	Earth Resources Observation System
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FIRE	First ISCCP Regional Experiment
GCM	Global Climate Model
GCRP	Global Change Research Program
GEWEX	Global Energy and Water Cycle Experiment
GLAS	Geoscience Laser Altimeter System
GLI	Global Imager
GOES	Geostationary Operational Environmental Satellite
GOMI	Global Ozone Monitoring Instrument
GOMOS	Global Ozone Monitoring by Occultation of Stars
GSFC	Goddard Space Flight Center
HCFC	Hydrochlorofluorocarbon
HDF	Hierarchical Data Format
HIRDLS	High-Resolution Dynamics Limb Sounder
HIRS	High-Resolution Infrared Sounder
IASI	Infrared Atmospheric Sounding Interferometer
ICF	Instrument Control Facility
IGBP	International Geosphere-Biosphere Program
IELV	Intermediate Expendable Launch Vehicle
IEOS	International Earth Observing System
ILAS	Improved Limb Atmospheric Spectrometer
IMB	Investigator of Micro-Biosphere
IMG	Interferometric Monitor for Greenhouse Gases
IMS	Information Management System
IPCC	Intergovernmental Panel on Climate Change
IPOC	International Partner Operations Center
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project
IST	Instrument Support Terminal
ISTG	
JEOS	Japanese Earth Observing System
JERS	Japan's Earth Resources Satellite
JGOFS	Joint Global Ocean Flux Study
JPL	Jet Propulsion Laboratory
LAGEOS	Laser Geodynamics Satellite
Landsat	Land Remote-Sensing Satellite

LaRC	Langley Research Center
LAWS	Laser Atmospheric Wind Sounder
LIDAR	Light Detection and Ranging
LIS	Lightning Imaging Sensor
LITE	Lidar In-Space Technology Experiment
MCP	Meteorological Communications Package
MELV	Medium Expendable Launch Vehicle
MERIS	Medium-Resolution Imaging Spectrometer
METOP	Meteorological Operational Satellite
MHS	Microwave Humidity Sounder
MIMR	Multifrequency Imaging Microwave Radiometer
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MISR	Multi-Angle Imaging SpectroRadiometer
MITI	Ministry of International Trade and Industry
MLS	Microwave Limb Sounder
MODIS	Moderate-Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
MOS	Marine Observation Satellite
MSFC	Marshall Space Flight Center
MTPE	Mission to Planet Earth
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (Japan)
NCAR	National Center for Atmospheric Research
NDSC	Network for Detection of Stratospheric Change
NOAA	National Oceanic and Atmospheric Administration
NSCAT	NASA Scatterometer
NSIDC	National Snow and Ice Data Center
OCTS	Ocean Color and Temperature Scanner
ORNL	Oak Ridge National Laboratory
PGS	Product Generation System
POEM	Polar-Orbit Earth Observation Mission
POES	Polar-Orbiting Operational Environmental Satellite
POLDER	Polarization and Directionality of Earth's Reflectances
POLES	Polar Exchange at the Sea Surface
PR	Precipitation Radar
PRAREE	Precise Range and Range Rate Equipment—Extended
QC	Quality Control
RA	Radar Altimeter
Radarsat	Radar Satellite
RIS	Retroreflector in Space
S&R	Search and Rescue
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar
SBUV	Solar Backscatter Ultraviolet
SCARAB	Scanner for the Radiation Budget
SCF	Science Computing Facility

SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SeaWiFS	Sea-Viewing Wide Field Sensor
SEDAC	Socio-Economic Data and Applications Center
SELV	Small Expendable Launch Vehicle
SEM	Space Environment Monitor
SIR-C	Shuttle Imaging Radar-C
SLIES	Stratospheric Limb Infrared Emission Spectrometer
SMC	System Management Center
SMMR	Scanning Multispectral Microwave Radiometer
SOLSTICE	Solar Stellar Irradiance Comparison Experiment
SSALT	Solid-State Altimeter
SSBUV	Shuttle Solar Backscatter Ultraviolet
SSM/I	Special Sensor Microwave/Imager
TBD(J)	To Be Determined Japanese Instrument
TDRSS	Tracking and Data Relay Satellite System
TERSE	Tunable Etalon Remote Sounder of Earth
TES	Tropospheric Emission Spectrometer
TIROS	Television Infrared Observing Satellite
TMI	TRMM Microwave Imager
TMR	TOPEX Microwave Radiometer
TOGA	Tropical Ocean Global Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOMUIS	3-D Ozone Mapping with Ultraviolet Imaging Spectrometer
TOPEX	Ocean Topography Experiment
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measuring Mission
UARS	Upper Atmosphere Research Satellite
UNEP	United Nations Environment Program
USGCRP	U.S. Global Change Research Program
VIRS	Visible Infrared Scanner
WCRP	World Climate Research Program
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
X-SAR	X-Band Synthetic Aperture Radar