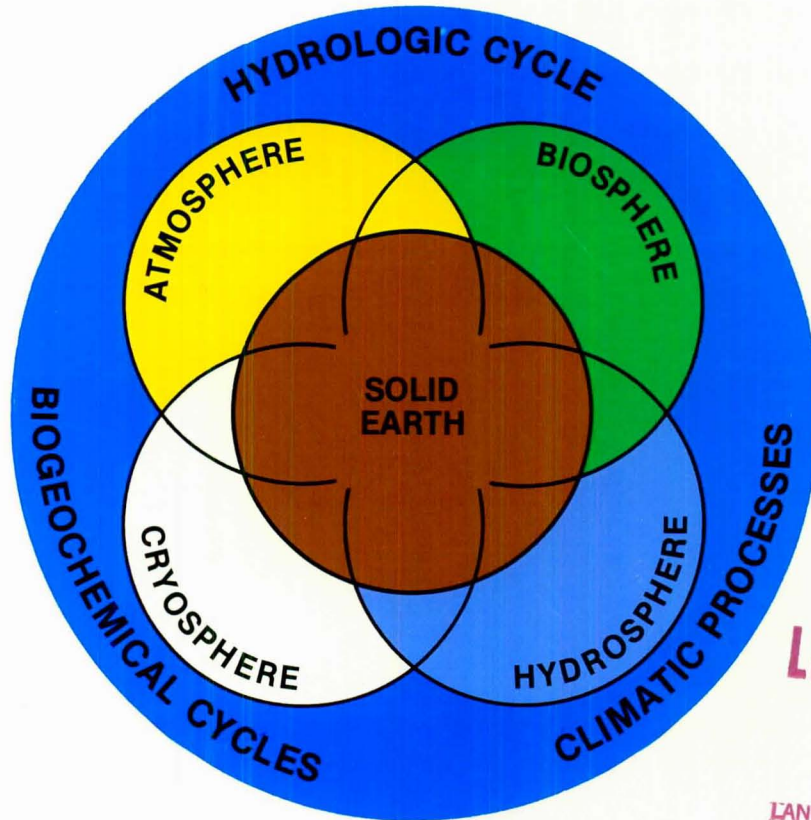


Technical Memorandum 86129

EARTH OBSERVING SYSTEM



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Science and Mission Requirements
Working Group Report

Volume I (Part 1 of 2)

FOR REFERENCE



National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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**SCIENCE AND MISSION REQUIREMENTS
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EXECUTIVE SUMMARY

Over the last decade or so several problems in Earth science have emerged which require a multidisciplinary approach. Examples include the increase in atmospheric carbon dioxide, the anticipated depletion of the ozone layer, El Niño related modifications to weather patterns, and acid precipitation. The key to progress on these and other interdisciplinary issues in Earth science during the decade of the 1990s probably will be addressing those questions which concern the integrated functioning of the Earth as a system. The fundamental processes which govern and integrate this system are the hydrologic cycle, the biogeochemical cycles and climate processes, and each of these includes physical, chemical, and biological phenomena. There will also be considerable opportunity for progress on many questions which are the province of one or more of the traditional disciplines of Earth science. In fact, research on the integrating themes will be built upon a foundation of progress in research along established disciplinary lines. Table 1 of the following report highlights science questions which have been distilled from the work of many advisory committees and other groups, these problems represent prime candidates for a well integrated program of multidisciplinary research.

In order to address these multidisciplinary problems confronting Earth science, observational capabilities must be employed which range in scale from detailed *in situ* and laboratory measurements to the global perspective offered by satellite based remote sensing. In this study of a potential future mission for NASA, our focus has been primarily upon space observations but with a clear recognition that satellite obtained data must be used in concert with data from more conventional techniques. A number of the parameters of the natural system must be measured including the composition and dynamics of the atmosphere, the dynamics and biological activity of the ocean and inland waters, the distribution of sea and land ice, the distribution of both biological and geological regimes over the land surface, and the underlying structure of the planet. Since many of the important changes at work in the Earth system have time scales of seasons to years, persistent observations of dynamic phenomena are needed to build data records which stretch over a decade or more. Therefore, we have tried to plan a future mission which will provide global data covering the required variety of feasible remote sensing measurements for the appropriate time period while affording an opportunity for coordination with the various types of more localized measurements which are requisite to complete the observational suite of the system.

In trying to provide long-term data records, one must start with what is already available before developing new systems. The now operational land and meteorological satellite systems have provided over a decade of

observations many of which are crucial to the research questions confronting us. The first step must be to ensure that these key observations are preserved. The second step is to provide improved access to these data for scientific purposes. Third, a capability at least equal to the present system must be continued. Based on the foundation of these three steps we can examine what improvements and new systems should be undertaken. Based upon both our judgement and published recommendations by other groups, it is clear that NASA should proceed with the currently planned series of discipline oriented missions: UARS, TOPEX, ISTP, and GRM. Each of these missions will address a first order need for observations to answer a focused set of research problems in one or more disciplines. At the same time we would assume that the operational satellite capability would be up-graded through the flight of the Navy and NASA N-ROSS mission and improvements in atmospheric temperature and moisture sounders. Several foreign research satellites are also planned or are under development and international cooperation is as much a part of obtaining the complete set of satellite data as it is obviously essential to achieving complimentary global ground based measurements. This set of existing and planned activities which should form the basis for the mission we describe, is outlined in Table 3 of our report.

The understanding of the global integrated functioning of Earth will require observing and analysis systems which go beyond those which will be provided by the activities discussed above. The main thrust of our report is to describe an Earth Observing System (EOS) which we propose as an information system to meet many of these needs for remote sensing from low earth orbiting satellites and for a data system to ensure that the resultant data will be extensively exploited in combination with other observables. We recommend that the data system be initiated as soon as possible to improve access to existing data for research. Using current data streams in this way ensures that the data system is prepared for the improved and increased flow of data which will come from the new sensors we envision. Over the decade of the 1990s a set of thirteen new measurement capabilities should be placed on orbit in a series of synergistically related groups or packages. When this full set is completed it should be operated in combination for a decade or more to enable a comprehensive examination of the Earth as a system.

The set of instrumentation placed on orbit should begin with an automated data collection and location system to enable improved use of buoys and other automated localized measurement systems. The other twelve capabilities which are described in our report should be thought of as a candidate list of current devices. The specific characteristics of these twelve instrument concepts and the motivation for their combination into three

groups are given in Chapter III of the report and summarized in Table 4. We recommend flight of these instruments in a sun-synchronous orbit with a 2.00 pm equator crossing time. If some of these observations were to be made on operational or other research satellites, there would be no need for duplicating them on an EOS spacecraft provided that the data could be accessed by the Earth science community. Conversely, we have assumed the existence and improvement of the operational system. If some key measurement such as atmospheric sounding were not adequately measured operationally, an instrument would need to be added to the EOS complement to provide research quality observations.

We state our conclusions and make five recommendations in the final chapter of this report. First and foremost, it is essential that the existing data be preserved, the existing observational capability be sustained, and that the planned research missions and operational improvements be carried out. This would include flight of instruments with observational capabilities similar to those

we describe which go beyond current plans. Second, access to existing, planned, and future data must be easy and cost effective if efficient progress is to be made in understanding the Earth. Third, the base of current research activity must continue as a foundation for new systems. Fourth, NASA should develop the Earth Observing System as an information system mission including new sensors in low Earth orbit and a data system to serve the needs of an integrated multidisciplinary study of the planet. Fifth, NASA should continue to avail itself of the advice of the scientific community in guiding the development and operation of EOS. It should be remembered that this new endeavor will not meet every need of Earth science research, in particular, it does not address the needs for observations from geosynchronous orbits, from small, specialized orbiters, or from non-orbiting devices. However, the Earth Observing System has the potential to revolutionize our understanding of the world around us.

PREFACE

A report such as this is shaped by the circumstances which have led to its commissioning, by the process and ground rules involved in its development, and by the related efforts which have preceded it

In the early spring of 1981, Dr. Burton I. Edelson, NASA Associate Administrator for Space Science and Applications, commissioned an intense in-house study of what could and should be done on a polar orbiting platform to provide a new observational capability to satisfy integrated Earth science measurement needs. He asked Mr. Pitt Thome to pull together a group of NASA scientists to carry out this study and report back in six months or less. Mr. Thome named the activity System Z and selected a committee composed of David Atlas, Robert Hudson, James Dunne, Wayne Mooneyhan, Albert Rango, Ann Kahle, Donald Krueger, Mitchel Rambler, William Piotrowski, and Dixon Butler, who served as executive secretary of the group. This group reported back that the concept of a polar platform to support a set of highly capable remote sensing instruments had great promise for serving Earth science and applications. A strategy for implementation was formulated, including recommendation of synergistic groupings of instruments and alternative concepts for platform design. One strong conclusion of this study was that the data system would ultimately be the key to success. A number of presentations of these findings were given, including one to NASA Administrator James Beggs. As a result, a decision was made by Dr. Edelson to have the Earth Science and Applications Division at NASA Headquarters go forward with an expanded study of this idea.

A study project office was established to implement this study, and the System Z (now EOS) Science and Mission Requirements Working Group was formed. The individual members were selected to represent the various traditional disciplines of Earth science. The charter of our group was to examine the major Earth science questions for the 1990s and to define the requirements for low Earth orbit observations needed to answer these questions on a comprehensive, multi-disciplinary basis. Our charter did not limit our consideration to either a platform or a polar orbit. As our study proceeded, we found it essential to define an information system to meet the global needs of Earth science research. This information system is our definition of the Earth Observing System and

includes a data system and various measurement systems. In accord with our charter, we have confined our consideration of observing systems to those appropriate for low Earth orbit, but we believe that other required measurement systems would logically be included in the information system we propose.

We would not have been able to synthesize the concerns and needs across the full spectrum of Earth science were it not for a number of reports prepared by other groups. Helpful reports from the various boards and committees of the National Academy of Sciences include

- Towards the Science of the Biosphere
- Global Tropospheric Chemistry: A Plan For Action
- Data Management and Computation: Volume 1, Issues and Recommendations
- A Strategy for Earth Science from Space in the 1980s, Part I: Solid Earth and Oceans
- A Strategy for Earth Science from Space in the 1980s and 1990s, Part II: Atmosphere and Interaction with the Solid Earth, Oceans, and Biota
- El Niño and the Southern Oscillation: A Scientific Plan
- Ocean Research for Understanding Climate Variations—Priorities and Goals for the 1980s
- Changing Climate
- Two Special Issues in Satellite Oceanography: Ocean Dynamics and Biological Oceanography
- Toward an International Geosphere-Biosphere Program—A Study of Global Change

Specific satellite studies produced by NASA committees which have also helped guide us are as follows:

- Satellite Data Relay and Platform Locating in Oceanography
- Guidelines for the Air-Sea Interaction Special Study: An Element of the NASA Climate Research Program
- Science Program for an Imaging Radar Receiving Station in Alaska
- The Marine Resources Experiment (MAREX)
- Satellite Altimetric Measurements of the Ocean
- Scientific Opportunities Using Satellite Wind Stress Measurements over the Ocean
- Ice and Climate Experiment
- Sea Ice Mission Requirements for the US FIREX and Canadian RADARSAR Programs

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I. INTRODUCTION

Earth science research is now ready for a unified approach based upon the view that the physical, chemical, and biological processes at work on Earth comprise a coupled global system. Traditional divisions of Earth science continue to work to understand limited regions of the planet or specific processes, but the number of research problems requiring contributions from many different fields has grown substantially in recent years. This growing commonality of interest among Earth science disciplines suggests that plans for future satellite observations be made by a multidisciplinary group. This is the approach we have taken. This report assesses the key issues and directions in Earth science and recommends that an advanced information system, including a data system and new observing facilities, be established to pursue a comprehensive multidisciplinary approach to understanding Earth as a system. We call this proposed entity the Earth Observing System (EOS). We have translated the major scientific questions confronting us into characteristics required of both measurements and a data system. A significant subset of these measurement requirements has been further translated into candidate groupings of instruments and mission parameters which are appropriate for space activities in the 1990s.

We conclude that the present moment presents a large set of opportunities and challenges. These arise from the confluence of three factors:

(a) *Multidisciplinary Scientific Problems*—A number of new scientific questions have emerged over the last two decades which cut across traditional disciplinary boundaries within Earth science. Key examples are the El Niño phenomenon, ozone layer modification, increases in atmospheric carbon dioxide, and acid precipitation. There are also problems that have been the subject of prolonged study and for which new observational approaches now appear promising. These new approaches often involve measurements which are applicable to several problems in different disciplines.

(b) *Instrumentation Opportunities*—For a variety of reasons, the deployment of new instrument technologies in space has not kept pace with the development of state-of-the-art instrument capabilities. Several of these technologies promise to break new ground in the understanding of the processes controlling the atmosphere-biosphere-hydrosphere-cryosphere-solid earth system, and they should be exploited in a timely way within the context of an overall measurement strategy. Recent research has shown that instruments such as AVHRR, HIRS II, and MSU, which were designed primarily for meteorological investigations, are useful in certain ecological, oceanographic, and climatic investigations. Early results of this work are illustrated in Figure 1. New techniques and multidisciplinary planning offer promise of many additional cases where an instrument can meet many needs.

(c) *Data Systems*—The remarkable development of improved capabilities for the transmitting, processing, and storage of data offers the Earth scientist a new hope of being able to comprehend the overall natural system of the planet. The growth in computational power is permitting researchers for the first time to express quantitatively their understanding of many dynamic phenomena through numerical models and to use these models to predict the future from a scientific basis. The quantity of affordable computer power which can be put at the disposal of the individual scientist can literally stretch his ability to comprehend and greatly increase his productivity. The data system technologies which will be available by the 1990s will enable us to cope with the vastness of Earth and the constant changes taking place in the natural environment on the level of detail at which we need to observe.

SCIENCE ISSUES

Earth science is a maturing research field where much is known about a variety of detailed processes, but where the broad integrating themes and understanding are just now beginning to take shape. The past two decades have seen major progress with the concepts of dynamic meteorology and plate tectonics. Both developments required new observational techniques. With comparable improvements in measurement capabilities, breakthroughs appear possible in the understanding of ocean circulation and upper atmospheric processes during the 1980s. The decade of the 1990s will provide opportunities for similar progress on scientific problems that require an integrated approach to the study of Earth. This decade will also provide the opportunity to obtain simultaneous measurements of parameters relevant to energy disposition, hydrologic status, and chemical cycles on a global basis. Key examples of research areas which will benefit from this approach are the role of the polar regions in climate, the large scale hydrologic cycle, global biology, and biogeochemistry. At the same time there will be many related opportunities for significant breakthroughs on questions in the traditional disciplines of Earth science.

In the solar system, our planet is distinguished from all others by the presence of water in abundant quantities in all of its three states—solid, liquid, and gas—and by the ability to sustain life. As Figure 2 illustrates, the view from space makes this obvious. The transport of water and the changes in its physical state are the cornerstone of the functioning of the Earth as a system, yet little quantitative information is available about the global hydrologic cycle. Thus, a central scientific issue is to quantify the processes, transport rates, and related reservoirs which comprise this cycle. Similarly, sustenance of life is dependent upon various chemical elements,

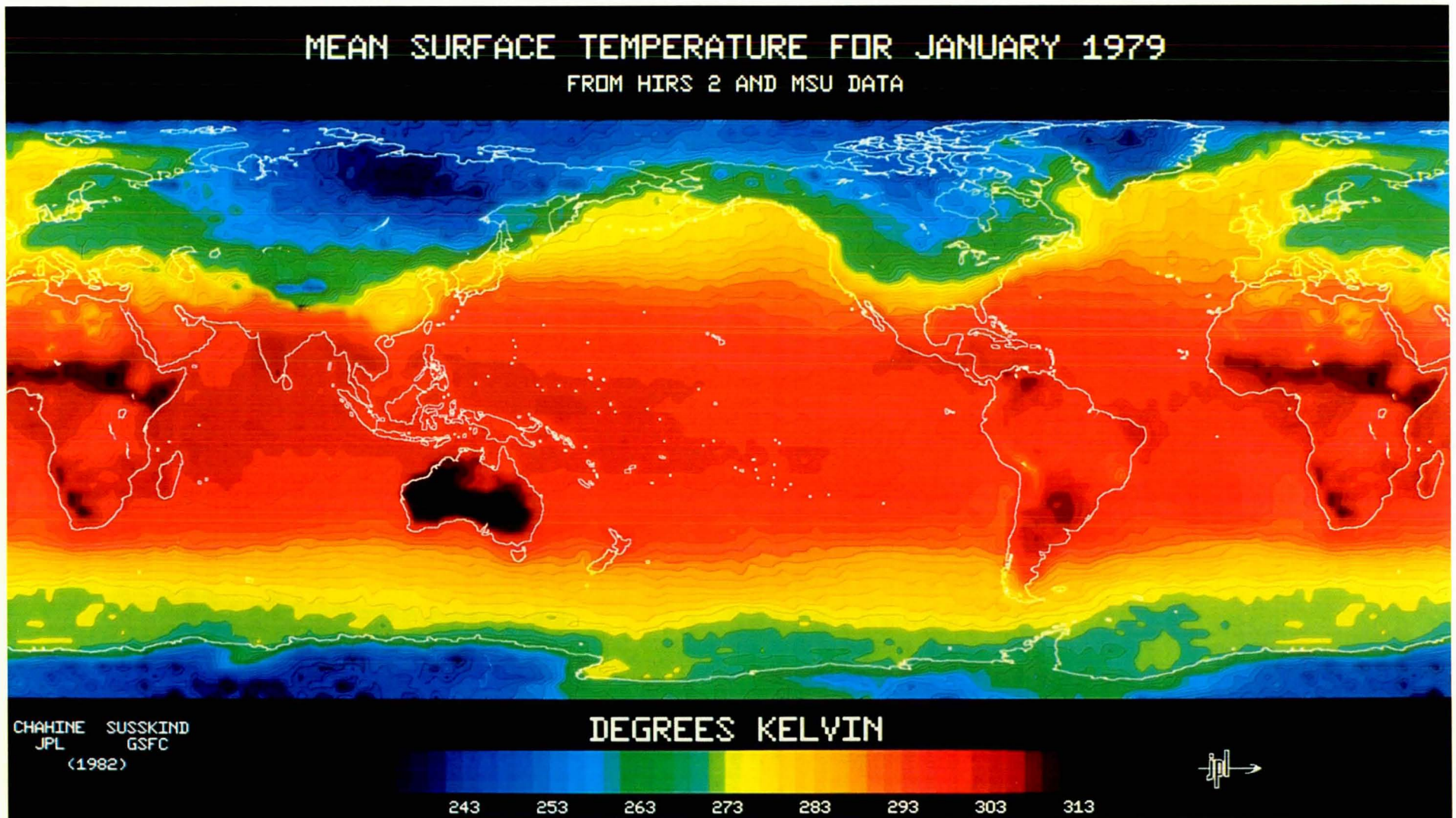


Figure 1. Global map of the Earth's mean monthly surface skin temperature for January 1979, from the High Resolution Infrared Sounder 2 and the Microwave Sounding Unit data. Skin surface temperature was derived from the 3.4 and 4.0 μm window channels on HIRS 2 in combination with additional microwave and infrared data from two Microwave Sounding Units.

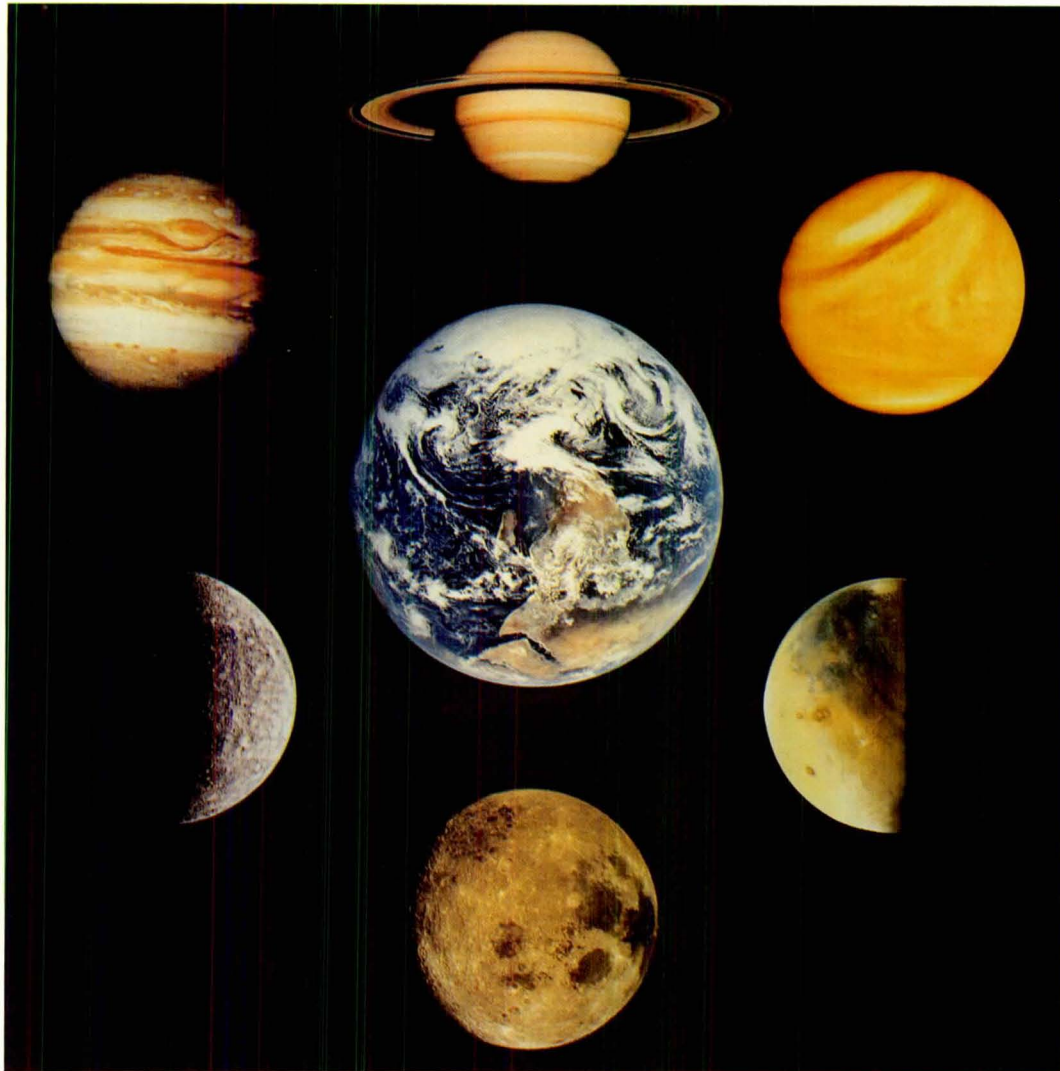


Figure 2. In the progression from barren, cratered rocks to totally shrouded gas giants, only Earth has the moderate conditions which provide abundant liquid water and partial cloud cover.

knowledge of their cycling through the environment is central to our understanding of life on Earth.

Energy and Water Cycles

A basic requirement for quantifying the transport rates of the hydrologic cycle is a knowledge of the distribution of net solar energy input to the Earth. Radiation is reflected, absorbed, scattered, and emitted by atmospheric gases, aerosols, clouds, and the planetary surface. Quantifying these processes requires knowledge of the global distribution of clouds and aerosols, surface radiative characterization of the land and ocean, and measurement of the extent and water content of ice and snow cover. Measurement of these dynamic properties is needed in addition to monitoring the more slowly varying concentrations of the radiatively active gases of the atmosphere.

Much of the energy which falls on the Earth is absorbed at the surface. The oceans store a large portion of this energy, and it is geographically redistributed by the circulation of the oceans and evaporation into the atmosphere. Understanding the role of the ocean in this process requires knowledge of the circulation of the oceans and the distribution and magnitude of their input of water vapor and latent heat to the atmosphere. Ocean circulation is largely determined by the influx and loss of thermal energy, the physical structure of ocean basins, the surface wind stress, and the sources and sinks of variation in salinity or density. Evaporation from the ocean is largely determined by sea surface temperature, sea surface wind speed, sea ice extent, atmospheric moisture, and atmospheric temperature structure.

Much less heat is stored over land, and heat transfer processes and evaporation from the land surface are more complex than those in the oceans due to the great variety

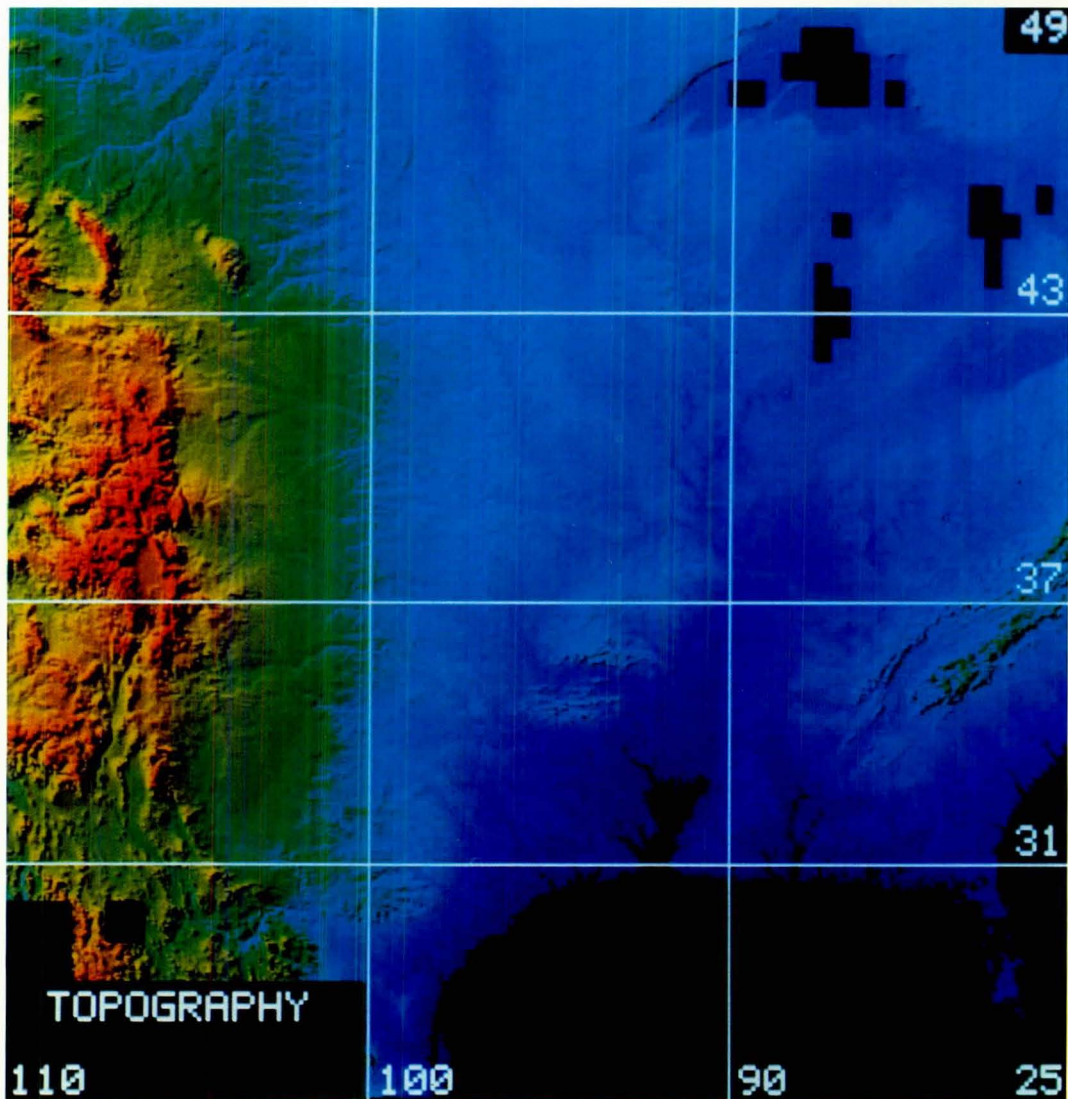
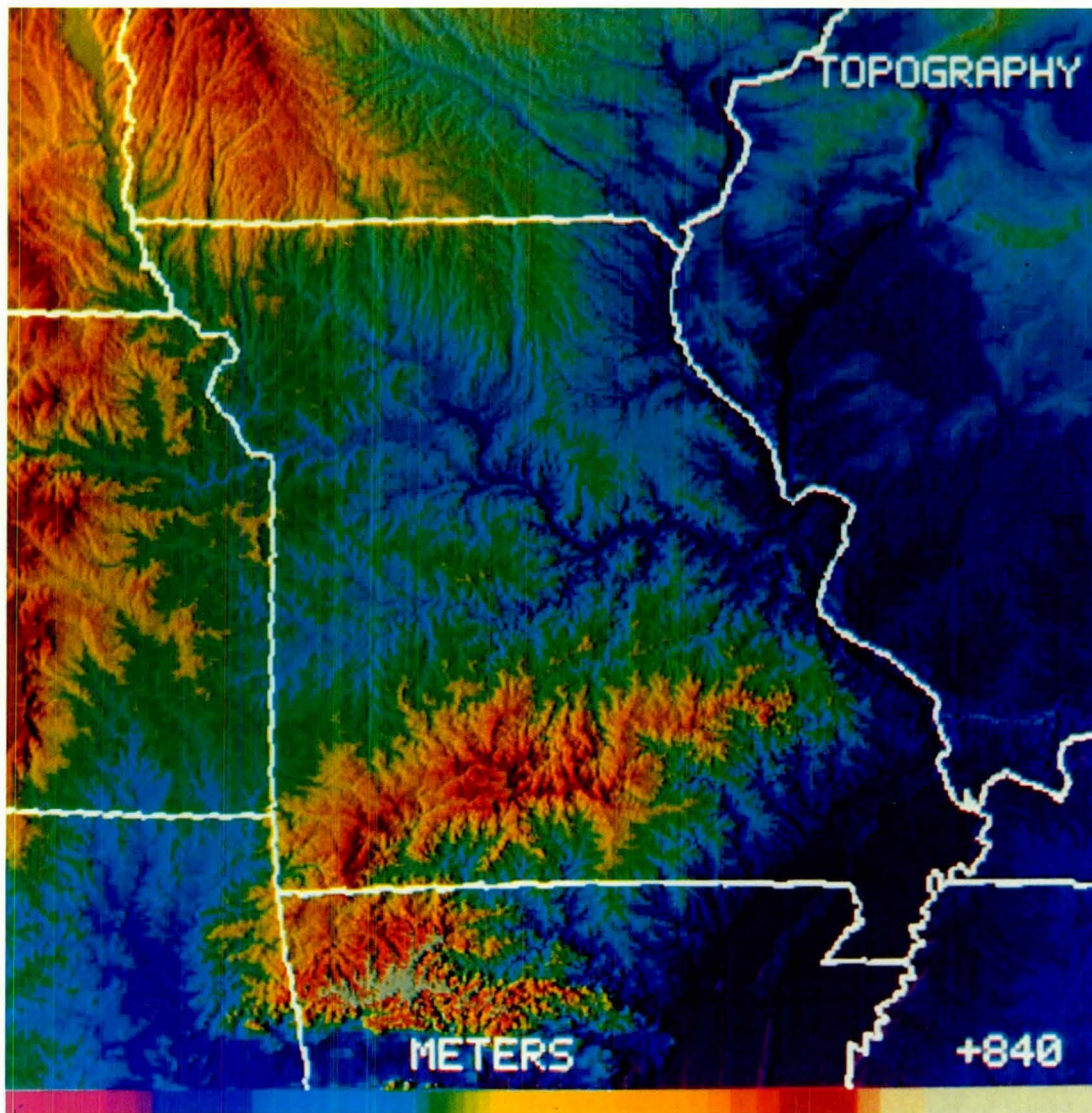


Figure 3. Image simulated from NOAA 1 km averages of topography for midcontinent (above) and for Missouri in color coded form (facing page). The continental-wide view (above) displays about 10% of the resolution of the Missouri view (facing page).

of land surface conditions. The global distribution of the different types of surfaces, their responses to energy input, and the magnitude and distribution of their inputs of water vapor to the atmosphere must be determined. As both the key to the geologic structure and history of Earth and the foundation for all land processes, the continents must be characterized in terms of the underlying rock units and their structure, the consequent soil type and structure, and the surface topography. All of these characteristics have a pronounced influence on the land component of the hydrologic cycle. Figure 3 shows to-

pography at two different scales of resolution. The coarse resolution is clearly not sufficient for use in this multidisciplinary study, but the finer resolution is unavailable for most of the land surface of the Earth. Establishing the global distribution of all the different biomes from wetlands to deserts is also a key requirement. The actual transfer of water to the atmosphere will depend upon varying conditions including surface moisture content, solar radiation, physical and physiological state of any vegetation present, wind speed, atmospheric temperature, and humidity.



Once water has evaporated, it is transported by the circulation of the atmosphere and provides a source of latent heat through condensation to enhance atmospheric motions and storms. This moisture content is a major variable in the net input of solar energy to the ground through the formation of clouds and in the infrared cooling of the atmosphere through the emissions of water molecules. A key question in meteorology remains when, where, and how much it will rain? This process closes the atmospheric portion of the water cycle. At present, the means for quantifying rainfall on a global basis do not have the required accuracy or geographic coverage.

The last element of the water cycle is the runoff from the land into the oceans. Runoff is influenced by temporary storage in the soil, snow pack, inland ice, and lakes. Storage capacities for these reservoirs must be

determined along with the discharge through the various river, estuary, and ice discharge systems of the world in order to quantify this piece of the cycle. Thus, to quantify and understand the global hydrologic cycle as illustrated in Figure 4, a significant set of related concerns in geology, oceanography, meteorology, glaciology, aquatic and terrestrial ecology, and climatology must be addressed.

Biogeochemical Cycles

The flow of water and energy through the environment is fundamental to an understanding of the biogeochemical cycles of elements such as sulfur, phosphorus, carbon, and nitrogen. These elements, together with oxygen and water, are the principal building blocks of

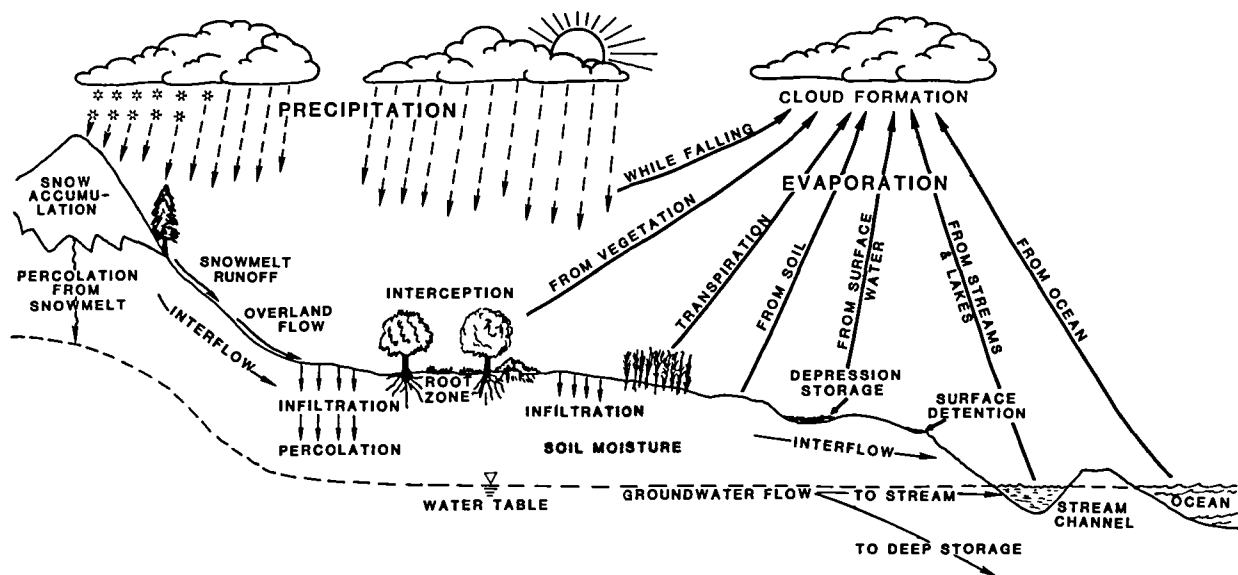


Figure 4. Processes in the global hydrologic cycle.

life The key concern of biogeochemistry is the interaction of the geological, physical, chemical, and biological processes which control the flow and transformation of chemical elements in the Earth system. Much of the transport and many of the reactions of carbon, nitrogen, phosphorus, and sulfur occur in solution within organisms and in the inland waters, oceans, and atmosphere. The intimate interconnection of the water and biogeochemical cycles is graphically illustrated in Figure 5, which shows the confluence of the nutrient-poor Rio Negro and the fertile Rio Solimões to form the Rio Amazonas.

In addition to the quantification of the water and energy cycles, understanding the biogeochemistry of Earth requires knowledge of the rates of biological processes and the capacity and size of various chemical reservoirs. This includes determination of the primary biological productivity of oceans and land biomes, the amounts of various compounds carried by rivers, and the fluxes of different gases both into and out of the atmosphere. Figure 6 illustrates the problems entailed in achieving a global measure of productivity. The currently available data are clearly unsatisfactory. The role of human practices in these processes, as well as catastrophic natural phenomena such as volcanic eruptions, must be understood.

That the ultimate fate of such biologically-produced gases as nitrous oxide and methane is determined primarily in the upper atmosphere is an example of the interconnected nature of the Earth system. In the stratosphere, these substances, along with water, participate

in a complex interaction of chemical processes, radiation, and dynamic processes which control the amount and distribution of the ozone layer and the upper reaches of the atmospheric circulation system. The ozone layer determines the ultraviolet transmission properties of the atmosphere, and the amount of ultraviolet radiation reaching the surface has direct effects on living systems. Second, some ozone is transported from the stratosphere and serves as one source of tropospheric ozone. In the troposphere, ozone is a key compound in the chemistry of trace constituents and is an oxidant directly affecting the surfaces of living organisms.

A further example of the complex interconnections among the components of the Earth system is provided by the sulfur cycle. As recent volcanic eruptions have demonstrated, the primary source of sulfur in the environment at times can be processes relating to degassing of the earth. Once in the air, sulfur is transformed into sulfuric acid, which can return to the surface through both wet and dry deposition. This acid deposition can potentially alter the pH of the soil and water, and affect both the type and amount of biological activity which takes place in a given region. The acid in the atmosphere is further transformed into particles or aerosols which can significantly alter atmospheric radiative transmission properties. Therefore, understanding this cycle requires measurements of both biological, anthropogenic, and geophysical sources, an understanding of atmospheric chemistry and the gas-to-particle conversion process, and the determination of how the Earth's surfaces interact with atmospheric sulfur gases and aerosols.

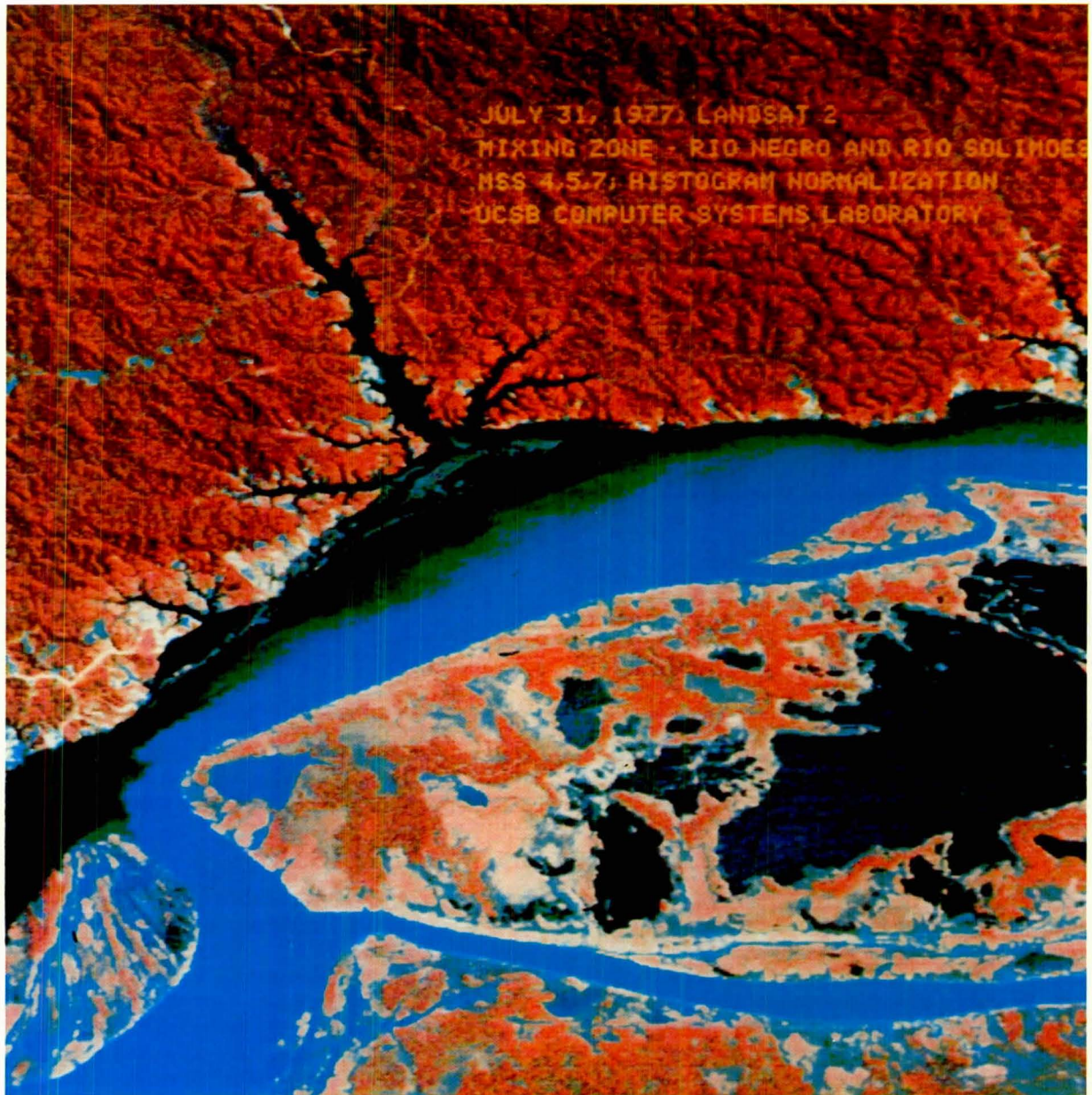


Figure 5. False color composite of Landsat Multi-Spectral Sensor Image of confluence of Rio Negro (black) and Rio Solimões (blue) to form the Rio Amazonas in the central Amazon basin. Image taken 31 July 1977 as the river levels were falling. The land around the rivers and lakes is tropical rainforest (red) and agricultural fields (pink, grey); the city of Manaus is adjacent to the west.

Today much widespread concern over global climate centers on the increase of carbon dioxide in the atmosphere due to alterations in the carbon cycle. This gas is an important infrared absorber in the atmosphere, and therefore, it reduces the rate of energy transmission from

Earth to space. Plants remove carbon from the atmosphere to build organic compounds over their lifetimes, and much of this reduced carbon remains in detrital reservoirs. Bacteria and other agents of decay and oxidation recycle some of this carbon into the environment,

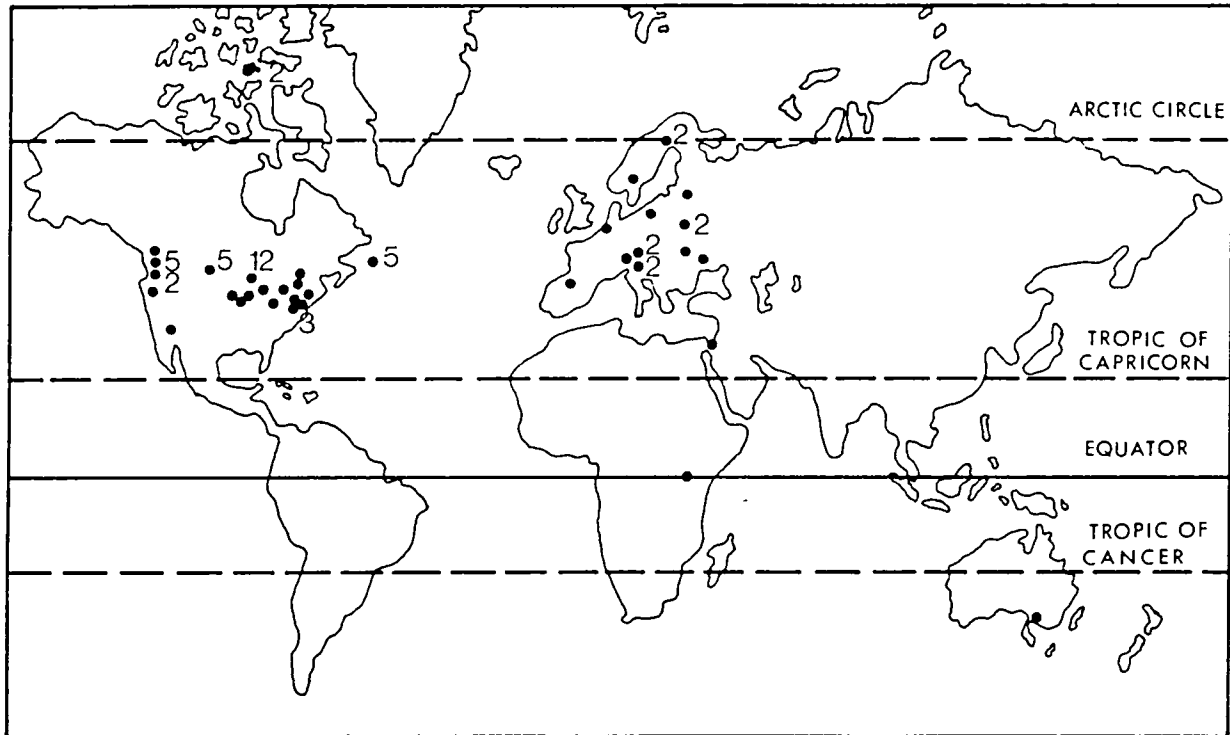


Figure 6. Location of lakes (●, numbers indicate several lakes in same locality) used by Schindler (Limnol. Oceanogr. 23: 478-486, 1978) in an analysis of factors regulating phytoplankton production and standing crop. Lakes from everywhere in the world with productivity, standing crop, and nutrient loading data were included. As Schindler stated, the data are "highly biased toward glacial lakes in north temperate and subarctic regions . . . More complete data are needed for water bodies in tropical and arctic regions, in the southern hemisphere and in unglaciated areas before a definitive global analysis of production and factors affecting it can be made."

largely as carbon dioxide. The burning of carbon-based fuels has the same effect. Since most of this fuel represents fossil carbon that was stored long ago over millions of years, its rapid release into the atmosphere will raise the carbon dioxide concentration of the atmosphere for long periods of time. Throughout most of the atmosphere, carbon dioxide is chemically inert. Thus the atmosphere serves mainly to transport it from sources to sinks. The source and sink strengths are determined by the biological activity and physical processes at work in the ocean and on land. The answer to the carbon dioxide question requires adequate measurements to establish that the rates of these processes can be calculated on a global scale.

Geologic History

The Earth today is a product of a four-and-a-half-billion-year process of evolution. Nature has already run a number of Earth science experiments. The results of some of these are stored in those aspects of the planet which are slow to change. At long time scales, the

underlying geologic structure of the crust and lithosphere can reveal how the continents and ocean floor have evolved over time. This subsurface memory can be unlocked in part through measurement of the detailed structure of the gravitational and magnetic fields. The sea floor provides a record stretching back 200 million years, but the continual process of formation and subduction removes any longer-term evidence from this record. The surface topography and distribution of continental rock units reveal additional evidence of geologic activity and past surface structure back to almost 4 billion years ago. Thus, study of the crustal structure of the oceans provides information on recent tectonism, while examination of the continents provides information extending much further back in geologic time. In addition, this structure underlies all the past operations of climate processes.

Ice cores, ocean sediment, and glacial deposits preserved in continental rocks are currently man's best keys to paleoclimate and unfold a pattern of warmings and coolings on various time scales stretching back to 2.5 billion years. Explanation of these variations is one possible test of any theory of contemporary climate change.

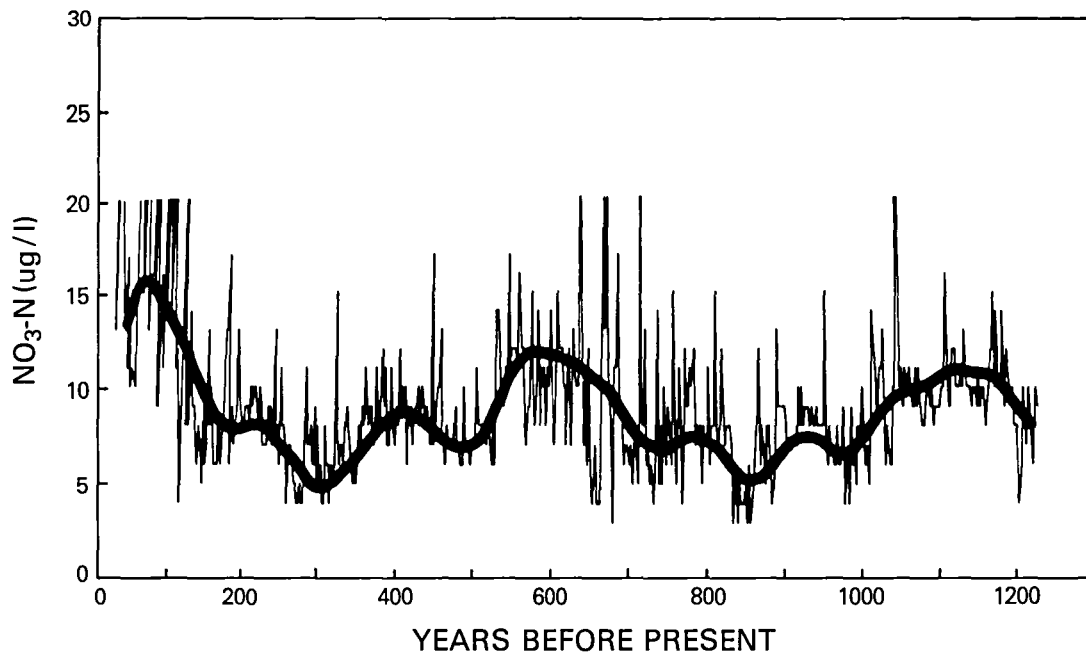


Figure 7. Variation of nitrate concentration over the past 1,200 years measured in an ice core from the South Pole station. The time scale is approximate and based on the average snow accumulation rate. Data points are approximately half yearly, and the heavier smoothed curve brings out longer-term changes. Parker, Zeller, and Gow consider likely controlling factors are galactic cosmic rays for background, solar-mediated auroral for the 11-year and longer-period fluctuations, and giant solar flares for major spikes. Reproduced by permission of the International Glaciological Society from *Annals of Glaciology* 1982, V. 3, pp. 2-3.

On shorter time scales, written records, tree rings, and cultural artifacts raise questions about the variations in phenomena such as solar activity and glaciation. As an example, Figure 7 shows the variation of nitrate concentration over the past 1,200 years as measured in an ice core from the South Pole.

Electrodynamic Processes

Plasma processes involving electric and magnetic fields and charged particles dominate the outer regions of the Earth's atmosphere and its near-space environment. These processes are also present in all regions of the Earth system. Through the temporal and spatial gradients of the Earth's magnetic field, these plasma phenomena are influenced by the workings of the core of the planet and the electromagnetic structure of the crust. Lightning and auroral activity are both known to be sources of atmospheric trace constituents, primarily nitrogen oxides. There are also direct connections among ionospheric structure, lightning in storms, surface electric fields, and the electric currents which run through the land surface and oceans. The significance of these plasma phenomena in the evolution and current functioning of the Earth system needs to be determined.

Climate

In principle, all of the above bear on the question of climate—its short-time, interannual variations and its change over longer time periods. Records of the past written on paper, in tree rings, in sea floor and ice cores, and in the rocks, have clearly shown that climate does change. Our problem is that we have no working theory of climate. Climate has been described as the average weather, but this average weather is controlled by the boundary conditions to the atmosphere more than by its present state.

Each of the disciplines included in this report provides information about some climate system boundary conditions. A particular boundary condition is a reflection of a budget for a given environmental property or constituent and processes which control the magnitudes of the terms within that budget. Virtually every budget and the processes which control it depend on others due to the interaction among the atmosphere, hydrosphere, biosphere, cryosphere and solid earth, and external forcing from the Sun. This interrelation is illustrated schematically on the cover.

In order to advance our understanding of climate, these interactions with their feedback links must be better

quantified. For climate research, the Earth Observing System will provide a much more complete data base on these boundary conditions and the processes which control them. Easy access to data will advance progress toward a more comprehensive information base from which a quantitative theory of climate and its variations and changes on time scales important to our civilization can be established.

Summary

Much is known about the Earth, but the unifying concepts are still only beginning to be established. An exposition of the key issues in Earth science is neither simple or concise. One can conclude from the scientific

questions at hand that there are many interconnections among them and that the view of the Earth as a system is essential to their solution. The appendix contains more in-depth expositions of the scientific questions from the viewpoints of the several areas of Earth science research. Table 1 lists what we feel are the key unifying science issues and questions for the 1990s. In the past, questions about the Earth at this level of breadth might well have been too general to serve as a foundation for productive research. However, much progress in our understanding of our planet and the emergence of several global environmental controversies have served to bring this unified approach to the forefront and recommend its use in future planning for scientific research.

TABLE 1 Earth Science Goals for the 1990s

HYDROLOGIC CYCLE

- Quantify the processes of precipitation, evaporation, evapotranspiration, and runoff on a global basis
- Determine what factors control the hydrologic cycle
- Determine the effects of sea and land ice upon the global hydrologic cycle
- Quantify the interactions between the vegetation, soil, and topographic characteristics of the land surface and the components of the hydrologic cycle

BIOGEOCHEMICAL CYCLES

- Understand the biogeochemical cycling of carbon, nitrogen, phosphorus, sulfur, and trace metals
- Determine the global distribution of biomass and what controls both its heterogeneous distribution in space and its change over time
- Determine the global distribution of gross primary production and respiration by autotrophic and heterotrophic organisms and the annual cycle and year-to-year variation of these processes
- Determine the transport of sediments and nutrients from the land to inland waters and ocean
- Quantify the global distribution and transport of tropospheric gases and aerosols and determine the strengths of their sources and sinks in the ocean, land surface, coastal and inland waters, and upper atmosphere
- Understand the processes controlling acid precipitation and deposition

CLIMATOLOGICAL PROCESSES

- Determine the modes of large-scale and low-frequency variability (month-to-month and year-to-year time scales) of meteorological variables such as wind, pressure, temperature, cloudiness, and precipitation
- Quantify the large-scale and low-frequency variability of net incoming solar radiation and net outgoing long-wave radiation and their relationships to cloudiness
- Determine the relationships between large-scale and low-frequency variability of meteorological observables and the variability of sea surface temperatures and current systems
- Quantify the influences of changes in land surface evaporation, albedo, and roughness on local and regional climate
- Assess the influence of sea and land ice cover on global climate
- Improve and extend knowledge of past climates
- Determine the role of land biota as sources and/or sinks of carbon dioxide and other radiatively important trace gases
- Predict climate on a probabilistic basis

GEOPHYSICAL PROCESSES

Atmospheric

- Understand the coupling of the chemical, radiative, and dynamic processes of the troposphere, stratosphere, and mesosphere
- Determine the coupling between the lower and upper atmosphere
- Improve the quantitative understanding of the variability of atmospheric ozone, including the influence of anthropogenic perturbations
- Improve understanding of the mechanisms for the maintenance and variability of atmospheric electric fields
- Improve the accuracy of deterministic weather forecasting and extend the useful forecast period

Oceanic

- Measure the mesoscale to large-scale circulation of the ocean and acquire a better understanding of the long-term variability in this circulation
- Determine the global heat, mass, and momentum coupling between the ocean and atmosphere
- Understand the processes controlling the dynamics of sea ice and its interaction with the underlying water
- Determine the upper ocean response to thermal and atmospheric forcing, including the effects of persistent horizontal variability in the ocean and atmosphere
- Understand the interaction of physical and biological processes, including the effects of horizontal and vertical variability
- Characterize the exchange processes between surface and deep waters

Solid Earth

- Determine the global distribution, geometry, and composition of continental rock units
- Understand the causes of the morphology and structure of the continental crust
- Understand how episodic processes such as rainfall, runoff, dust storms, and volcanism modify the surface of the earth
- Understand the dynamics of inland ice sheets
- Determine the relation between the factors of climate, topography, vegetation, and the geologic substrata and the processes of soil formation and degradation
- Understand the secular variation in plate velocities
- Determine the planform, vertical structure, and time variation of mantle convection
- Measure the global gravity and magnetic fields to reveal with greater accuracy and resolution the structure of the lower crust and upper mantle lithosphere
- Explain secular variations, including reversals in the Earth's magnetic field
- Explain secular variations in the Earth's long wavelength gravity field in terms of the viscosity structure of the mantle

II. OBSERVATIONAL REQUIREMENTS AND MEASUREMENT SYSTEMS CONCEPTS

In developing our recommendations for addressing the science needs presented in Chapter I, a number of broad concepts have proven useful. First, observables of the system can be classified as *quasi-static* or *dynamic*. Examples of the former include the distribution of rock-types, land surface elevations, broadly categorized vegetation regimes, gravity and magnetic fields, and topography of large land ice bodies. Such features need to be mapped, in some cases at relatively high spatial resolution, but the needed repeat time for mapping is several years or longer. Although many of these quasi-static aspects of the Earth system have been measured, improvements in precision, coverage, and/or spectral and spatial resolution are needed to solve current research problems. The second category involves phenomena which vary on time scales of minutes to seasons or decades. This category includes most atmospheric and sea surface quantities, the detailed properties of many types of vegetation, snow cover, sea ice, suspended organisms and sediments, surface energy balance quantities, precipitation, and soil moisture. In general, such quantities need systematic, consistent, and frequent measurements with continuity over long time periods.

There are a variety of systems available from which to carry out Earth science observations. Each type has its own unique advantages and limitations, and the choice of which to use is usually strongly related to the temporal and spatial scales of the phenomena being measured. *In situ* observations are important in all areas of Earth science to measure the small-scale processes and to provide correlative confirmation of remote sensing measurements. They are also essential in the study of phenomena at all scales whenever remote sensing techniques are unavailable or infeasible. *In situ* observations require putting the instrument where the phenomena to be measured are taking place. This in turn requires measurement systems ranging from taking cores of the Earth's crust and of ice sheets to use of submarines, ships, buoys, aircraft, balloons, rockets, and satellites. Remote sensing offers the opportunity to view processes on a larger and more comprehensive scale. Remote sensing instruments must be taken to where they can obtain the view and coverage required to study the desired phenomena.

In providing viewing and coverage on regional to global scales there is seldom any substitute for satellites as observational systems. However, each orbit in which satellites can fly provides a unique combination of temporal and spatial coverage. Low earth orbits provide a relatively closeup view suitable for active measurement techniques, namely radar and lidar, and facilitate high spatial resolution observations. The inclination of the orbital plane determines the relative balance between the extent of the coverage and the frequency of observation. A purely equatorial orbit provides an overpass of a given

location roughly every one hundred minutes, but misses all of the Earth which cannot be seen from directly over the equator. A nearly polar, sun-synchronous orbit provides coverage of virtually the entire surface of the Earth but only at two fixed times of day. This orbit is often chosen for Earth observations and is particularly appropriate for observing phenomena which are sufficiently persistent to permit observation only every twelve or twenty-four hours. It provides near-global coverage and relatively consistent illumination conditions, but virtually all observations are made at two fixed local times. Day and night contrasts can be measured, but the full cycle of diurnal variations is not sampled. This can greatly bias measurements of rapidly changing phenomena.

As the altitude of an orbit is increased, the ability to see more of Earth increases, but the size of the instrument optics required to achieve a given resolution grows. The period of the orbit also increases with altitude, so that at an altitude of roughly 36,000 km the orbital period is one day, and an equatorially orbiting satellite stays over the same location on the Earth's surface at all times. The orbit is geostationary and provides coverage of a region roughly one-fifth of the planet between 60 degrees North and South latitudes. This is an ideal situation for observing short time scale phenomena and for sampling at all times of day. In this way the geostationary orbit is an excellent complement to the sun-synchronous low Earth orbit. There are also useful orbits in between. The temporal and spatial scales required by the observation, together with the type of instrument needed, dictate which orbit is suitable. In summary, there is no single ideal orbit.

A second broad concept is that instrument techniques can be grouped into three broad categories according to the readiness of the technology involved. Established instruments are those for which the physical relationship between the measurement and the geophysical parameters to be measured is clearly understood and the engineering feasibility has been demonstrated. In the second category are instrument concepts for which the relationship between the observable and the desired geophysical parameters is generally understood but the engineering feasibility is not yet fully demonstrated. The third class includes promising instrument concepts for which the relationship between the desired geophysical quantity and the observable remains to be clarified. This may be because of inadequately understood physics or because of the need for complex modeling involving significant uncertainties to obtain the geophysical parameters from the data. Instruments in all three categories need to be developed.

In designing an implementation strategy and outlining the set of needed observations and the data system which

will comprise the Earth Observing System, it is important to put them in the context of other satellite measurement systems. There are several planned scientific missions which should take place in the late 1980s and early 1990s. EOS as an observation system must be viewed as a successor to these wherever appropriate. EOS as an information system should incorporate data received from these missions. There is a continuing and potentially growing set of operational satellites which will be taking scientifically useful data in the EOS time frame of the 1990s. In general there is no need to provide a redundant source of these data, but access to these data for research must be ensured.

A common thread underlying the majority of Earth science research problems is the need to gain sufficient understanding of the environment to allow reliable predictions to be made. Such predictions may include the prediction of natural variations of one component of the system in response to variations in another component. Significantly, prediction also includes responses to anthropogenic perturbations. Thus for many observables, it is necessary both to establish a baseline in order to categorize with precision the present state of the system and, at the same time, to obtain concurrent time series of globally distributed observables in order to establish the characteristics of fluctuations and trends.

ELEMENTS OF AN OBSERVATIONAL STRATEGY

These considerations lead us to propose six philosophical elements that a measurement strategy for dynamic quantities should contain. Some, though not necessarily all, of these elements apply as well to quasi-static quantities.

(1) Systematic Global Observations

From the nature of the research problems described in Chapter I, it is clear that long-term observations of the atmosphere-ocean-land-cryosphere system are required. Meteorological and Earth resources data which have been collected and treated as "operational" data are essential research data and should be treated as such. Easy access to these data is crucial, and any observational research strategy must pay close attention to the continuity, coverage, processing, quality control, archiving, and application of these data to science problems. Ongoing observational programs, even if they are routine in character, should be adequately maintained as long as they continue to serve an important function.

(2) Nested Coverage

For many problems there is a need for detailed lo-

calized coverage at higher resolution than is feasible on a global basis with frequent repetition. Such data can serve three essential purposes: (a) building up global high resolution maps of quasi-static variables over a long period of time while optimizing for viewing conditions, (b) providing detailed views of localized regions with comparatively short repeat cycles in order to provide a basis for interpreting changes seen at lower resolution, or in order to provide data bases for specialized local studies, and (c) providing detailed observations for the development of parameterization schemes to enable detailed processes to be inferred from the coarser resolution data. Careful attention needs to be paid to optimizing such nested coverage, and to integrating the concomitant capability for flexible observations into an observational program. Without careful planning, requirements associated with flexible observing can easily overwhelm other elements of an observational program.

(3) Continuous Upgrading of Observational Capability and Testing of Promising Instrument Concepts

As the systematic global observational data set continues to grow in time, improvements in the observational system which could be made using state-of-the-art technology should be incorporated on a timely basis. Thus, as improved precision, reliability, or stability become possible, the observing system should reflect all of these changes which meaningfully improve the research capability of the system. For the interdisciplinary problems which we are considering, it seems likely that much future emphasis will be on measurements of properties of the surface and interactions between the surface and the atmosphere. As scientists become aware that more capable sensors based on well-understood instrument concepts are needed, new instruments should be developed to address these needs. Some new instruments will require on-orbit tests prior to becoming the sole provider of some crucial data series. It is essential that such relatively straightforward upgrading steps be made taking full account of the need to maintain long-term continuity in the data record. This requires intercalibration and in many cases periods of overlapping use.

(4) Orbit Considerations

As discussed above, different processes require observation on differing spatial and temporal scales. Frequently changing phenomena, such as severe storms and rain, cannot be adequately characterized without the virtually continuous observations of geostationary orbit. High resolution and active remote sensing are more easily implemented in low Earth orbit. Therefore, measurements must be judged as to their appropriateness for

the frequency of sampling which can be achieved from the orbit selected. Also, satellites should be used for their unique capabilities, not for measurements which can be better made by other means

(5) Quality Control: Data Validity and Management

Guarantees of the quality of the data being obtained must be an integral part of any strategy of research observations. Adequate procedures for checking observational accuracy and precision must be developed and maintained. These will generally involve repeated or sustained instrument calibration and some sort of correlative data, ideally involving a limited number of *in situ* measurements. In some cases, full-scale field programs will be needed to establish the relationships between instrument observables and the desired physical properties of the natural system.

Relationships between some observables and desired physical quantities will be statistical in the sense that retrieval of the physical variables from remote sensing data cannot be made from first principles. In such cases, the statistical relationships or indices may themselves depend on the state of the system, and a limited but long-term set of *in situ* data will be needed. It is important that provision be made for such cases.

Another component of quality control occurs in data processing and archiving. These functions should be structured in such a way as to enhance the ease with which data sets, including "operational" data sets, can be used in research carried out by a variety of investigators. They should also be structured to ensure continuity and a reasonable degree of uniformity in the data archive, and to ensure that future improvements in data processing technology can be applied with a minimum of disruption and a reasonable degree of economy.

(6) Data Interpretation

It is likely that the most severe limitation on the establishment of satellite observation systems in the 1990s will be in the area of final science interpretation. The problems are extensive and must involve many investigators from diverse disciplines working cooperatively. Provision must be made early to ensure that the necessary scientific capabilities are assembled in time. Innovative approaches are needed to foster the type of interdisciplinary research needed to fully capitalize on EOS data. As mentioned above, easy access to data is essential to achieve high scientific productivity. The investment of money and management attention to provide this access is as important as the investment in flight hardware and the satellite system to carry it. The data system must be in place and operating before significant new streams of data are initiated.

CRITERIA FOR DETERMINING AN OBSERVATIONAL PROGRAM

In relating measurement capabilities to the major scientific issues at hand and in advancing a measurement strategy incorporating the elements outlined above, the following set of criteria have guided our thinking. They should continue to be helpful in refining the definition of an observational program.

- (1) Significance of the primary scientific questions.** The primary questions to be addressed by particular combinations of instruments should be highly significant to several areas of Earth science or essential to a single discipline. A set of observations which promises to resolve crucial scientific issues in several areas of Earth science deserves priority over isolated investigations.
- (2) Technical readiness.** Clearly the likelihood of achieving significant scientific understanding is high if significant problems can be addressed with established technology. The ability to use existing instruments or observing systems in novel ways promises earlier, more reliable answers to science questions.
- (3) Potential of undeveloped techniques.** If the observational requirements to resolve a significant scientific issue cannot be met with current techniques, new measurement capabilities must be aggressively pursued even if the requisite technology requires considerable development.
- (4) Engineering and economic feasibility** should be considered at every stage of planning for an observational program. It would be unrealistic to ignore the role of possible long development times and high costs in dictating the mix of instruments to be flown in satellite observing systems in the 1990s. However, a significant investment had to be made to obtain the current measurement capability, and major improvements will virtually always require significant additional investment.
- (5) Data access and data systems.** Existing data may provide answers to some questions, therefore, it is prudent to ensure that current data and historical archives are easily accessible to the scientific community as a whole. In the design of future endeavors, data systems and measurement devices must be designed and developed in tandem so that they reinforce one another in the ultimate goal of providing information to advance scientific understanding.

III. IMPLEMENTATION STRATEGY

INTRODUCTION

It is clear from the foregoing discussion of key scientific research questions that the Earth Observing System must be, in and of itself, a major international undertaking, and a significant new thrust in Earth science as a whole. The interdisciplinary themes which link various scientific fields together are, to a large extent, major elements of complex international endeavors, such as the World Climate Research Program. Consequently, the implementation of a program such as EOS requires that considerable attention be given to organization and coordination capable of linking multinational projects (and their data sets) with a more focused activity—the Earth Observing System.

Meeting the identified needs of Earth science requires approaching EOS as an information system and not simply as one or more satellites with instruments. *In situ* measurement devices and networks, orbiting remote sensing instruments, and a data system must be fused into a highly capable research tool. Approaching this capability as a whole can ensure the maximum utility of each element.

The full range of global Earth science issues has been examined to put EOS in context with respect to the research needs of the individual scientific disciplines. The appendix provides this discussion in appropriate detail and is an important part of our report. There is a considerable duplication of observations desired by the specific Earth science disciplines. This is one of the strengths of the multidisciplinary approach. A consolidated list of the required observations is given in Table 2. In outline form, the table provides not only the observation needed but some of the driving requirements for these observations, periodicity of observation, and in some cases, the level of resolution or sensitivity. A large subset of these observations are obtainable from satellites in low Earth orbit. Requirements for active measurement techniques and high spatial resolution are important considerations that favor low Earth orbits. However, the high temporal resolution obtainable from geostationary satellites is recognized, and such orbits will be required for some observations such as rainfall.

Briefly stated, the strategy outlined in this chapter has six elements as follows:

- 1) Implement the individual discipline missions that are currently planned,
- 2) Make use of sustained observational capabilities offered by operational satellites without waiting for the launch of new missions, specifically NOAA, GOES, Landsat, non-U.S. geostationary meteorological satellites, and N-

ROSS, ERS-1, MOS-1, and other ocean-observing satellites (as they come into being),

- 3) Put first priority on the data system and have the required capability functioning prior to putting new assets in orbit,
- 4) Deploy an Advanced Data Collection and Location System to support and aggregate *in situ* observations,
- 5) Put a substantial new observing capability in low Earth orbit in such a way as to provide for sustained measurements over a decade or longer with flexibility to capitalize on new technologies,
- 6) Group instruments to exploit their capacities for synergism, maximize the scientific utility of the mission, and minimize the costs of implementation where possible.

Elements 1 and 2 form a foundation from which an Earth Observing System can carry out elements 3 through 6. The full resolution of the issues of Earth science will also require efforts beyond these, including the exploitation of enhanced geostationary observing capabilities as they become available. We believe that carrying out this strategy both during and before the 1990s is essential if mankind is to reap the benefits of understanding the functioning of the Earth as a natural system of which we are all a part. In order to build up the chain of interdisciplinary understanding, each of the major discipline links must be kept strong.

In this chapter, we first discuss steps that should be taken to prepare for EOS, including receipt and interpretation of new types of data, how existing and planned satellites fit into an overall science strategy, and how interdisciplinary science ties should be established. Three candidate payload packages are then described. We stress that these payloads are proposed for heuristic value and must be critically reexamined as further development of EOS proceeds. These instrument groupings have been chosen so as to acquire a variety of data pertinent to addressing specific objectives. Note that the intent is by no means to describe a fixed instrument package payload. Rather, as discussed in the beginning of this report, we feel it is important to maintain a capability to change instrumentation and to include new observational capabilities as they are developed. Thus, while we feel that the instrument groupings we have chosen provide significant synergistic benefits, we would not want to preclude either development or inclusion of new, innovative systems for acquiring data. We end the chapter with a discussion of requirements on the Earth Observing System as an information system, the configuration that we suggest extends from sensor to scientist.

TABLE 2 Observational Needs

PARAMETER	APPLICATION	ACCURACY		APPROACH	SPATIAL RES	OBSERVATION FREQUENCY	SPECTRAL RES
		DESIRED	REQUIRED				
Soil Features							
● Moisture	Hydrologic and geochemical cycles	5 moisture levels	5 moisture levels	Microwave Radiometer Model	1-10 km 30-1000 m	2 day 1 week	20 cm ± 1 cm 20 cm ± 1 cm
● Surface		5%	10%				
● Root Zone		5%	10%				
● Types-Areal Extent (peat, wet lands)	Geochemical cycles Agricultural & Forestry	10%	10%	Visible/SAR	30 m	annual	20 nm/50 nm
● Texture-Color	Agriculture & Forestry	10%	10%	Visible/SAR	30 m	annual	20 nm/50 nm
● Erosion	Geochemical cycles	10%	10%	Visible/SAR	30 m	annual	20 nm/50 nm
● Elemental storage	Geochemical cycles	10%	10%	Visible/SAR	30 m	monthly monthly	20 nm/50 nm 20 nm/50 nm
● Carbon		10%	10%				
● Nitrogen		10%	10%				
● Permafrost	Geochemical	10%	10%	Visible/SAR	30 m	annual	20 nm/50 nm
Surface Temperature							
● Land	Primary production, soil moisture and respiration	0.5°C	± 1°C	Thermal IR	1 km ± 0.5 km	12 hours	50 nm
● Inland Waters	Mass/Energy Flux	0.1°C	0.5°C	Thermal IR	30 m	12 hours	50 nm
● Ocean	Mass/Energy Flux	0.1°C	0.5°C	Thermal IR, Microwave	4 km (open ocean) 1 km (coastal ocean)	12 hours 12 hours	
● Ice	Mass/Energy Flux	0.5°C	1°C	Microwave, Thermal IR	1 km	1 day	
Vegetation							
● Identification	Hydrologic cycle, biomass distributions and change, primary production, plant productivity, respiration, nutrient cycling, trace gas, source sinks, vegetation-climate interaction, microclimate	1%	5%	Visible, Near IR, Thermal IR	1 km	7 day	10-20 nm
● Areal Extent		1%	10%	Visible, Near IR, Thermal IR	30 m	30 day	30 nm
● Condition (stress, morphology, phytomass)		10%	15%	Visible, Near IR, Thermal IR, SAR	30 m	3 day	10-20 nm
● Leaf area index canopy structure and density		10%	20%	Visible, Near IR, Thermal IR, SAR	30 m	3 days	50 nm
Clouds							
● Cover	Radiation balance, weather forecasting, hydrologic cycle, climatologic processes, tropospheric chemistry	2%	5%	Visible, Thermal IR	1 × 1 km 1 km	6 hours 6 hours	
● Top height		± 25 km	± 5 km				
● Emission temp		± 5°C	± 1°C	Thermal IR	1 × 1 km	6 hours	
● Albedo		± 0.01	± 0.02	Visible	50 × 50 km	6 hours	
● Water Content		0.5 kgm/m ²	1 kgm/m ²	Microwave	50 × 50 km	6 hours	
Water Vapor	Weather forecasting, hydrologic cycle, climatologic processes	001 ppm	002 ppm	Microwave, Thermal IR, Lidar	100 × 100 km × 100 mbar (vertical)	12 hours	

TABLE 2 Observational Needs—Continued

PARAMETER	APPLICATION	ACCURACY		APPROACH	SPATIAL RES	OBSERVATION FREQUENCY	SPECTRAL RES
		DESIRED	REQUIRED				
Snow							
• Areal Extent	Hydrologic cycle	5%	10%	Visible/Microwave	1 km	7 days	0.6-0.7 μm/1 cm
• Thickness	Water equivalent	5%	10%	Microwave	1 km	7 days	3 bands, 0.8-3.0 cm
Radiation							
• Shortwave	Surface energy budget	2%	5%	Visible	1 × 1 km	1 day	
• Longwave	Surface energy budget	2%	5%	Thermal IR	1 × 1 km	1 day	
• Short & Long wave	Hydrologic cycle	2%	5%	Visible, Thermal IR	100 × 100 km	6 hours	broadband
Precipitation	Hydrologic cycle	5%	10%	Microwave or in situ	1 km	daily	several bands, 0.1-10 cm
	Climatologic cycle	5%	10%	in situ	1 km	daily	
Evapotranspiration	Hydrologic cycle	5%	10%	Thermal IR, Visible, Microwave combination (model)	1 km	daily	multiple sensors
Runoff	Hydrologic cycle	10%	10%	Thermal IR, Visible, Microwave combination (model)	—	daily	multiple sensors
Wetland Areal Extent	Hydrologic cycle	2%	5%	Visible, Thermal IR	30-100 m	monthly	multiple bands
	Biogeochemical cycle	10%	30%	Visible, Near IR/SAR	30 m	3 days	20 nm/2 radar bands
Phytoplankton	Biogeochemical cycles						
• Chlorophyll		10%	20%	Visible, Near IR	4 km/1 km/30 m	2 days	10-30 nm
• Fluorescence		10%	20%	Visible, Near IR	4 km/1 km/30 m	2 days	5-15 nm
• Pigment groups		10%	20%	Visible, Near IR	4 km/1 km/30 m	2 days	10-20 nm
Turbidity	Biogeochemical cycles						
• Inland water/coastal ocean	Erosion assessment	10%	20%	Visible, Near IR	30 m/1 km	2 days	10-30 nm
Bioluminescence	Ecological processes	presence/absence		Visible	4 km	monthly	10-20 nm
Wetland areal extent	Biogeochemical cycle	10%	30%	Visible, Near IR, SAR	30 m	3 days	three bands/20 nm
Surface Elevation							
• Land	Continental tectonics and surface processes	1 m	5 m	Laser or radar altimetry or stereo-photogrammetry, SAR altimeter, 1 meter, laser altimeter	100 m IFOV	10 years	
	Interpretation and modeling of gravity and magnetic field data		± 3 m (from averaging within 3 km blocks)		300 m × 300 m for averaging into 3 km blocks	10 years	
• Ocean	Circulation	1 cm		Microwave altimeter	25 km	2 days	
• Inland Ice	Hydrologic cycle	0.1 m	1.0 m	Altimetry	30 m	5 years	

TABLE 2 Observational Needs—Continued

PARAMETER	APPLICATION	ACCURACY		APPROACH	SPATIAL RES	OBSERVATION FREQUENCY	SPECTRAL RES
		DESIRED	REQUIRED				
Wave							
• Height	Air-Sea interactions	10%	10%	Scanning altimeter, SAR	50 km	3 days	
• Spectrum		± 10 degrees	± 20 degrees	Scanning altimeter, SAR	50 km	3 days	
Inland Ice							
• Thickness	Ice dynamics	1%	2%	Radar Sounding (probably airborne)	1 km	50 years	
• Velocity Field	Ice dynamics	5%	5%	SAR, ADCLS	one per 100 × 100 km	10 years	
• Mass Balance	Ice dynamics,	5%	10%	Thermal IR, Microwave,	one per 100 × 100 km	annual total	
Temperature	Hydrologic cycle, Climate	1 0°C	1 0°C	ADCLS		annual mean	
Sea Ice							
• Areal Extent	Hydrologic cycle	10 km	100 km	Microwave radiometer	5-20 km	weekly	
• Concentration	Oceanic processes	1%	10%	Microwave radiometer	1 km	bi-weekly	
• Sea Ice Dynamics	Climatological processes	10 m	100 m	SAR, ADCLS	100 m	daily	
Atmospheric Constituents (Ozone & Compounds of Carbon, Nitrogen, Hydrogen, Chlorine, Sulfur, etc)	Tropospheric chem	5%	20%	Dial/Correlation Spectrum	10 × 10 × 1 km	1 day	
	Middle atmosphere	5%	10%	Thermal IR, UV, etc	500 × 500 × 3.5 km	1 day	
	Upper atmosphere	10%	25%	Thermal IR, UV, etc	500 × 500 × 3.5 km	1 day	
Aerosols	Tropospheric chem	5%	20%	Lidar	10 × 10 × 1 km	1 day	
	Stratospheric chem	25%	50%	Lidar/Occultation	200 × 500 × 1 km	1 day	
Temperature	Troposphere	5° K	1° K	Thermal IR, Microwave, Lidar	100 × 100 × 5 km	1 day	
	Middle atmosphere	1° K	2° K	Thermal IR, Microwave	500 × 500 × 3.5 km	1 day	
	Upper atmosphere	5° K	10° K	Thermal IR, Microwave	500 × 500 × 3.5 km	1 day	
Winds	Troposphere		2 m/s	Doppler Lidar	100 × 100 × 3.5 km	12 hours	
	Middle atmosphere		3 m/s	Visible, IR (Interferometer)	500 × 500 × 3.5 km	1 day	
	Upper atmosphere		10 m/s	Visible, IR (Interferometer)	500 × 500 × 3.5 km	1 day	
	Surface	0.5 m/s	1 m/s	Scatterometry	50 km ²	1 day	
Lightning (number of flashes, cloud to cloud, cloud to ground)	Tropospheric chem , Atmospheric elect	stroke count	same	Visible to near IR Electromagnetic spectrum from ground	10 × 10 km 1 × 1 km	continuously continuously	
Emission Features	Upper Atmosphere	10%	25%	Near IR	10 × 10 × 3.5 km	10 minutes	
Electric Fields	Global electric circuit		10%	In situ electric field probe			
Rock Unit Mineralogy	Continental rock types	1% absolute	1% relative	Visible, Near IR-spectral reflectance	30 m pixel	10 years	10 nm, ~200 channels
	Continental soil and rock types and distribution	1° K (NEΔT)	3° K (NEΔT)	Thermal IR-spectral emissivity	30 m pixel	Seasonal coverage once every 10 years	6 channels, 8 to 14 μm, 500 nm, 2 channels, 3 to 5 μm, 500 nm

TABLE 2 Observational Needs—Continued

PARAMETER	APPLICATION	ACCURACY		APPROACH	SPATIAL RES	OBSERVATION FREQUENCY	SPECTRAL RES
		DESIRED	REQUIRED				
Surface Structure	Tectonic history	7dB SNR in image	5 db SNR in image	SAR	30 m radar cell width (4 looks)	yearly	variable incidence, variable frequency, variable polarization
Gravity Field	Mantle convection, oceanic lithosphere, continental lithosphere, sedimentary basins, passive margins, etc	0.5 mgal	1 mgal	gravity gradiometer tethered system, satellite tracking	<30 × 30 km	10 years	
Surface Stress	Weather forecasting, climate processes, oceanography	$u_* = 2.5$ cm/s	$u_* = 5$ cm/s	Radar scatterometer	50 × 50 km	12 hours	
Oceanic Geoid	Mantle convection oceanic lithosphere	0.5 cm	1 cm	Altimeter	1 km	10 years	
Magnetic Field	Crust & upper mantle, composition and structure, lithospheric thermal structure, secular variation of main field (core problem) upper mantle conductivity	0.5 nT	1.0 nT	Magnetometer, Magnetometer/gradiometer, tethered systems	<30 × 30 km	10 years	
Plate Motion	Plate tectonic theory, fault motion	0.5 cm in each component	1 cm in each component	Satellite tracking by radar laser, GPS, VLBI, ground transponder arrays in conjunction with satellite	Varies with problem, 1 km 1000 km	0.5 years in most cases, more frequently in areas of very active deformation	

STEPS TO PREPARE FOR THE EARTH OBSERVING SYSTEM

An important baseline for EOS is the initiation, launch, and sustained operation of the currently planned Earth science research missions UARS, TOPEX, GRM, and ISTP. The Upper Atmosphere Research Satellite (UARS) will address the questions of the coupling of chemical, radiative, and dynamic processes in the stratosphere and mesosphere. It will make measurements from a 57-degree orbit, which will enable it to study diurnal effects at the sacrifice of total coverage of the polar region. The mission is being designed to last for two years and may last longer, but the need for truly long-term measurements as identified by the scientific committee which originally proposed this mission will not be fulfilled unless there is a follow-on activity. UARS is a necessary precursor to EOS efforts to measure upper atmosphere parameters in a long time series on a global basis.

The Ocean Topography Experiment (TOPEX) will allow the time-variable and steady ocean currents to be determined to high accuracy, determining for the first time the general circulation pattern of the oceans. TOPEX will utilize radar altimetry from a 1300-km, 63-degree orbit. This is a needed scientific data set that can be obtained beginning at the end of this decade and that will provide the foundation for the determination of the long-term climatology of ocean circulation variations. Continuing this study is one test that EOS intends to undertake.

The Geopotential Research Mission (GRM) will determine both the magnetic and gravitational potential fields of the earth during a roughly six-month mission involving two satellites in a very low-altitude, exactly polar orbit. This information will be of use in interpreting ranging or altimetry data obtained on TOPEX and EOS, and addresses a scientific measurement need that requires *in situ* measurements from satellites of these potential fields.

The International Solar Terrestrial Program (ISTP) will utilize satellites in a variety of orbits to make *in situ* measurements of the plasma environment of Earth and remote measurements of the Sun. To the extent that this mission would overlap with EOS, the knowledge provided of the spatial distribution of particle inputs to the atmosphere would enable more precise study of their effects on the rest of the Earth system.

A number of long-term data sets are already being provided by operational satellites. The continuation of the NOAA, GOES, and LANDSAT series of satellites is crucial to the science of the Earth and is an essential basis for and complement to EOS. In general, data sets available for a given environmental parameter of the Earth system should continue to be acquired until new techniques for obtaining these data have been developed and implemented and the new data record overlapped with the old for intercalibration. In addition to this cli-

matological role, the operational satellites will provide significant contemporary data to EOS science investigations and will significantly reduce the needs for EOS to carry certain types of instruments. Specifically, NOAA and GOES satellites will provide cloud coverage, temperature soundings (hopefully with improved resolution and frequency), and limited resolution moisture soundings for understanding the atmospheric condition, the global distribution of precipitation, energy inputs, moisture, sea surface temperature, and the circulation patterns of the atmosphere. The LANDSAT could provide morning, high-spatial-resolution viewing of sites which EOS would view at another time of day with enhanced spectral resolution at both moderate and high-spatial resolution.

The Navy's planned N-ROSS satellite can be viewed as another research satellite which will provide important information for guiding the development of EOS. If it were to evolve into an operational series of ocean-observing satellites, the incorporation of research quality instruments in its payload could supplant the need for EOS to carry them, provided the data were readily available for scientific use. A key example of this possibility is the planned inclusion of a research-quality, six-antenna scatterometer in the N-ROSS instrument complement.

All of the data resulting from these missions will help form a basis for Earth Observing System activities. Table 3 describes the planned payloads and characteristics of these satellites as well as those planned by other countries. Foreign satellites have not been formally considered in this study, but they will make important Earth science observations, and coordination with these activities is highly desirable.

Data from research and operational satellites can be used to establish a well-defined and functioning data system which can begin by providing access to existing data streams as a means of demonstrating its ability to handle the flow of new data from EOS instruments. We recommend that the EOS information system be designed to access these data and, in some cases, include these data as part of the EOS data base.

The Earth science research community will require a sustained commitment of support if they are to be ready to utilize EOS data. The individual disciplines must be strong in order to assure a healthy multidisciplinary research environment. This will enable effective long-range planning consistent with the long-term need for baseline data set accumulation, ensure that mission planning is based upon scientific judgement, and provide stability which should not be disrupted by the more rapidly changing political environment.

The institutional and cultural settings within which most Earth scientists have traditionally worked encourage a focus on research in individual disciplines with only occasional interaction across discipline boundaries. For some EOS data and science objectives, this setting will remain satisfactory. However, the interdisciplinary

TABLE 3 Planned U.S. and Foreign Operational and Research Satellites for Observing The Earth

U.S. OPERATIONAL SATELLITES

NOAA WEATHER SATELLITES, 1978-1990s

Objectives operational weather data

Orbit sun-synchronous, 833 to 870 km, 7 00 a m & 2 00 p m equator crossing times

Payload

	NOAA	E	F	G	H	I	J	K	L	M	N	O	P
Advanced Very High Resolution Radiometer (AVHRR)	x	x	x	x	x	x	x	x	x	x	x	x	x
High Resolution IR Sounder (HIRS)	x	x	x	x	x	x	x	x	x	x	x	x	x
Stratospheric Sounding Unit (SSU)	x		x		x								
Microwave Sounding Unit (MSU)	x	x	x	x	x	x							
Data Collection System (DCS)	x	x	x	x	x	x	x	x	x	x	x	x	x
Space Environment Monitor (SEM)	x	x	x			x		x		x		x	
Solar Backscatter UV Exp (SBUV)		x		x			x		x		x		x
Earth Radiation Budget (ERB)		x	x										
Search & Rescue (SAR)	x	x	x	x	x	x	x	x	x	x	x	x	x
Advanced Microwave Sounder (AMSU)								x	x	x	x	x	x
Advanced Coastal Zone Color Scanner (ACZCS)									?		?		?
Planned or actual launch year		83	84	85	86	87	88	89	90	91	92	93	94
Equator Crossing Time (a m or p m)		am	pm	am	pm	am	pm	am	pm	am	pm	am	pm

Instrument Description

AVHRR 5 bands, 0.58 - 12.5 μm, 1 km/4 km res, 1,600 km swath, temperature of clouds, sea surface & land

HIRS/2 20 bands, atm sounding, temperature & moisture profiles

SSU 3 bands, atm sounding, temperature profiles

MSU 4 bands, 50.3 to 57.9 GHz, atm sounding

DCS random access from buoys, balloons & platforms

SEM 3 instruments, solar protons, alpha particles & "e" flux density

SBUV 12 bands, 2550 - 3400Å, solar spectrum, O₃ profiles, earth radiance spectrum

ERBE determine earth's radiation loss & gain

AMSU 20 bands, 10 to 90 GHz, possibly 180 GHz, all weather temp profiles

ACZCS 9 bands, 0.4-0.88 μm, 10.5 - 12.5 μm, ocean color, sea surface temperature

GOES - Geosynchronous Weather Satellite System, 1975 - 1990s

Objectives operational weather data, cloud cover, temperature profiles, real time storm monitoring, severe storm warning

Orbit geostationary at east and west

Payload Visible and Infrared Spin Scan Radiometer (VISSR), VISSR Atmospheric Sounder (VAS), Data Collection System (DCS), Space Environment Monitor (SEM)

Instrument Description

VISSR 2 band, 0.55-0.70 μm, 10.5-12.6 μm, 0.9km res visible, 8 km res IR, sensitivity of 0.4-1.4 K, day/night cloud cover, earth/cloud radiance temperature measurements

VAS 12 bands, 0.55-0.70 μm, 3.9-14.7 μm, day/night cloud cover, atmospheric temperature & water content

DCS random access from buoys, balloons & platforms

SEM solar protons, alpha particles, & "e" flux density

DMSP - Defense Meteorological Satellite Program, 1970s - 1990s

Objectives operational weather data for DOD

Orbit sun-synchronous, 720 km, equator crossing time as desired

Payload Operational Linescan System (OLS), Multispectral IR Radiometer (MIR), Microwave Temperature Sounder (MTS), Space Environment Sensor (SES) and Special Sensor Microwave Imager (SSM/I)

TABLE 3 (Continued) Planned U.S. and Foreign Operational and Research Satellites for Observing The Earth

Instrument Description

OLS 0.4-1.1 μm , 10-13 μm , 0.56 km/2.78 km res, global cloud cover
 MIR 9.8 & 12.0 μm bands, 13.4-15.0 μm (CO_2), 18.7-28.3 μm (H_2O), vertical temperature profiles
 MTS 50-60 GHz, seven band scanning microwave temperature sounder
 SES charged particle monitor
 SSMI 19.35, 37.0, 85.5 GHz, dual polarization, 22.23 GHz vertical polarization, 1,400 km swath, precipitation, soil moisture, wind speed over ocean & sea ice morphology

LANDSAT, 1972-1984

Objectives operational and data vegetation, crop & land use inventory
 Orbit sun-synchronous, 705 km, 9:30 a.m. node, 16-day repeat
 Payload Multispectral Scanner (MSS), Thematic Mapper (TM)

Instrument Description

MSS 5 band, 0.5-0.6 μm , 0.6-0.7 μm , 0.7-0.8 μm , 0.8-1.1 μm , 10.4-12.6 μm , 80 m res, 185 km Swath
 TM 7 bands, 0.45-0.90 μm (4), 1.55-1.75 μm , 2.08-2.35 μm , 10.4-12.5 μm , 30 m/120 m (10.4 μm) res, 185 km swath

N-ROSS- Naval Research Oceanographic Satellite System, 1988

Objectives operational sea state data for DOD/NASA research
 Orbit sun-synchronous, 830 km, TBD node, TBD repeat
 Payload Special Sensor Microwave Imager (SSM/I), Scatterometer (SCATT), Altimeter (ALT), Low Frequency Microwave Radiometer (LFMR)

Instrument Description

SSM/I 4 Freq 7 ch, 19.3, 22.2, 37.0 & 85.5 GHz, 102° scan view, 1394 km swath, 70 x 45 - 16 x 17 km IFOV, sea surface wind precip atm moisture, soil moisture and sea ice conditions
 SCATT 14.6 GHz, 6 antennas, dual/single pol, 50 km res, range 3 - 30 m/sec, accuracy 2 m/sec
 ALT SEASAT class, sea surface topography
 LFMR 2 bands, 5, 10 GHz, 6 M antenna, sea surface temperature

FOREIGN SATELLITES

SPOT - Systeme Probatoire, d'Observation de la Terre, 1985-Launch with Follow-On in 1987

Objectives operational land use and inventory monitoring system
 Orbit sun-synchronous, 10:30 a.m. node, 2.5 day repeat
 Payload SPOT

Instrument Description

SPOT 3 bands, 0.5-0.6 μm , 0.6-0.7 μm , 0.78-0.9 μm , 20 m res color mode, 10 m res panchromatic mode, (0.51-0.73 μm), 60 km x 60 km viewing area, swath of 950 km centered around nadir, stereoscopic images

MOS/LOS - Marine Observation Satellite - Land Observation Satellite (Japanese Program)

MOS-1 1986-1987, MOS-2-3 follow-ons
 LOS-1 1988-1989, LOS-2 follow-on
 Objectives MOS-color & temperature of sea surface, LOS-geological survey, land use, agriculture, forestry, disaster prevention
 Orbit sun-synchronous, 909 km, a.m. node, 17 day repeat
 Payload
 MOS-1 Multispectral Electronic Self Scanning Radiometer (MESSR), Visible and Thermal IR Radiometer (VTIR), Microwave Scanning Radiometer (MSR)
 MOS-2 altimeter, scatterometer
 LOS-1 Synthetic Aperture Radar (SAR), optical sensor

TABLE 3 (Continued) Planned U.S. and Foreign Operational and Research Satellites for Observing The Earth

Instrument Description

MESSR 4 bands, 0.5 to 1.1 μm , 50 m res, 100 km swath
 VTIR 4 bands, 0.5-0.7 μm , 6.0-7.0 μm , 10.5-11.5 μm , 11.5-12.5 μm , -1 km/3 km res, 500 km swath
 MSR 2 bands, 23.8 & 31.4 GHz, 317 km swath
 ALT SEASAT class
 Scatterometer 4-25 m/sec wind measurement, $\pm 20^\circ$ direction, 200 to 700 km swath
 SAR 1.2 GHz, 4 look angles, 25 m res
 Optical sensor TBD

ERS - 1 - ESA First Remote Sensing Satellite 1988-1989 Launch, ERS-2 Follow-On, ERS-3 Planned (European Program)

Objectives coastal ocean & ice studies, global weather, land use
 Orbit Sun-synchronous, 777 km, a.m. equator crossing time, 3 day repeat cycle
 Payload Active Microwave Instrument (AMI), Along Track Scanning Radiometer (ATSR)

Instrument Description

AMI SAR C band 5.3 GHz, 30 x 30 m res, 80 km-200 km swath
 Scatterometer (wind mode) 3 beam C-band, VV polarization, 500 km swath, 50 km res, range 4 m/s - 24 m/s, accuracy 2 m/s or 10%, scatterometer (wave mode) 5 km x 5 km image every 100 km, altimeter Ku band (12.5 GHz), 10 cm precision - land, 40 cm precision - ocean, 1.2 m diameter antenna
 ASTR radiometer, 3.7, 11 & 12 μm bands, 1 km x 1 km res, 0.1 k Res, 50 km swath,
 PRARE Precision Range And Range Rate Experiment, laser retroreflector

RADARSAT - Canadian Radar Program, 1990-2000, Three/Four Satellite Series

Objectives high resolution studies of arctic area, agriculture, forestry and water resource management, ocean studies
 Orbit sun-synchronous, 1,000 km altitude, 3 day repeat cycle
 Payload Synthetic Aperture Radar (SAR), Optical Sensor (TBD), Microwave Sensor (TBD)

Instrument Description

SAR C or L band, 150 km swath, 25-30 m res, 4-100 km look angles

U.S. RESEARCH SATELLITES

UARS - Upper Atmospheric Research Satellite, 1989 Launch

Objectives coordinated measurement of major upper atmospheric parameters
 Orbit 57° inclination, 600 km altitude
 Payload Cryogenic Limb Array Etalon Spectrometer (CLAES), Halogen Occultation Experiment (HALOE), High Resolution Doppler Imager (HRDI), Improved Stratospheric & Mesospheric Sounder (ISAMS), Microwave Limb Sounder (MLS), Particle Environment Monitor (PEM), Solar Stellar Irradiance Comparison Experiment (SOLSTICE), Solar-UV Spectral Irradiance Monitor (SUSIM), Wind Measurement in the Mesosphere (WINTER), Active Cavity Radiometer Irradiance Monitor (ACRIM), Solar Backscatter UV Experiment (SBUV)

Instrument Description

CLAES global synoptic measurement of nitrogen & chlorine ozone destructive species, minor constituents temperature
 HALOE stratospheric species concentration
 HRDI middle atmospheric winds
 ISAMS atmospheric temperature and species concentration
 MLS vertical profiles of O₃ & O₂, wind measurements, inferred pressure
 PEM charged particle entry measurements for atmosphere
 SOLSTICE solar irradiance from 1,150 to 4000Å

TABLE 3 (Continued) Planned U.S. and Foreign Operational and Research Satellites for Observing The Earth

SUSIM solar flux changes over 1,250 to 4000Å range
WINTERS temperature, wind and OH concentration
ACRIM solar constant monitor
SBUV vertical O₃ distribution

TOPEX - Topography Experiment 1989 Launch

Objectives ocean topography, ocean current signatures
Orbit 1,300 km , 63 4° inclination, 10 day repeat
Payload and Instrument Description

ALTIMETER 2 band, Ku - 13.5 GHz, C - 5.3 GHz, 2 cm precision, atmospheric correction provided by an on-board microwave radiometer

GRM - Geopotential Research Mission 1992, Launch

Objectives measure gravity and magnetic fields for tectonophysics, mantle convection, internal structure and composition, crustal magnetic anomalies, and main magnetic field models
Orbit 160 km circular, polar
Payload and Instrument Description

Two spacecraft using coherent Doppler radar (50 and 100 GHz) for satellite-to-satellite tracking Disturbance Compensation System Boom-mounted scalar and vector magnetometers on lead spacecraft

nature of the science opportunities which make the Earth Observing System desirable also demand that scientists begin to work across traditional boundaries by forming consortia and/or collaborative teams. Careful thought should be given as to the institutional and other arrangements necessary to foster such work. Several experimental and relatively small-scale projects could be initiated in the near future to test organizational approaches to these problems and how the use of new technologies could foster communication among research groups in different locations that are approaching the same objectives from different perspectives.

EOS DATA SYSTEM REQUIREMENTS

The first step in an evolving Earth Observing System must be the data system. While it is inappropriate to

attempt system design within this document, we can levy requirements on the data system from a science user's viewpoint. It is useful to divide the discussion into four categories: (a) data downlink, preprocessing, and delivery, (b) data archives, (c) scientific processing, and (d) mission planning and uplink activities.

With regard to the first category, we wish to assure that quality (well-documented, traceable) data are delivered to researchers for scientific processing and analysis. Consideration should be given to using "smart sensors" on EOS that can be commanded to downlink only the subset of acquired data that is needed over a given region. Data could be preprocessed to remove transmission errors and instrument-dependent aspects of the signals at a variety of distributed locations or at a central facility. We require that the scientists responsible for an instrument have the opportunity through the pre-

processing steps to fulfill their responsibilities of ensuring that the instrument is functioning properly and that the data are being interpreted correctly. Preprocessed data would then be made available to the community on a timely basis, where the time interval is defined according to the type of research being done and by mission constraints. For example, within atmospheric dynamics, a variety of EOS and *in situ* data might be needed within a short time interval to follow the progression of a particular weather system and to plan a new sampling strategy based on the resultant analyses. As part of this data delivery process, it is essential that algorithm development be started and that initial processing algorithms be in place before launch. A complete program for algorithm validation should also exist. Such a system for rapid data delivery will require an efficient cataloging system, for both quick perusal and long-term maintenance of the data sets.

The second category, data archives, deals with an area that must receive considerable attention if we are to exploit EOS data for global Earth science objectives. EOS data should be considered as an international as well as national resource. Appropriate care must be given to ensuring that the data are placed in a long-term, active archive, that documentation is included, that appropriate calibration files are appended, and that these data are efficiently accessible by the scientific community. That is, the data archive must ensure data continuity, comparability, and accessibility. The data should be accessible in several ways, such as by location or by time of acquisition. Standard algorithms should be included in the archive for general use by the community (e.g., algorithms such as general map projections, decalibration procedures). Consequently, the data should be included in a data base management system that incorporates access via location, time, sensor, or a combination of the three. Also, the data base management system must have the capability to update files, appending new and pertinent information. This system should also be able to interrogate distributed archives so as to avoid duplicate processing, particularly of higher-level data sets. A method to trace the processing steps performed on a particular piece of data should also be included.

Correlative data acquired by previous research experiments and satellites and by operational satellites, together with *in situ* data sets, must be accessible in the same manner as the EOS data. Since the thrust and scientific strength of EOS lies in its interdisciplinary themes, a broad spectrum of data will be required to solve a given problem. These data should be available through the EOS information system in a manner compatible with all other data sets. Thus EOS must support efforts to maintain and upgrade existing archives. In summary, the data base management aspects of the Earth Observing System are critical, since they could severely hinder scientific research if not thoughtfully implemented. With a geo-referenced, time series approach,

questions that were heretofore logistically difficult or perhaps unaddressable can be asked of the data and, hopefully, fundamental answers can be obtained.

For the third category, science processing, the requirement is to match computational requirements with research needs. Generally, decentralized, distributed processing is the trend today and most probably for the foreseeable future. A distributed processing approach has much to offer, since the science community which will be involved in the Earth Observing System will be distributed, and by the 1990s distributed processing may be the standard, accepted approach. This trend is due to lower costs for a given computational power, and the greater degree of customization and control that a researcher can achieve in his own facility relative to a centralized system. Although hardware costs and communications systems will likely allow EOS scientific processing to be done on a distributed system, software integrity and transportability must be ensured to alleviate development costs. Consideration should be given to developing well-documented software in higher-level languages which could be readily implemented at any number of diverse processing sites.

Past experience with satellite data for Earth science has been filled with difficulties coping with the logistical problems of locating and acquiring the proper data. If EOS overcomes these engineering problems, it will then be necessary to confront the challenge of comprehensive data interpretation. The sheer computational power required to handle global data sets, collected at frequent intervals for long time periods by multiple sensors, is enormous. For example, it is estimated that the proposed Ocean Color Imager will collect 100 times more data in two years than the Space Telescope will collect in five. Because one of the primary motivations for establishing EOS is the exploration of global interdisciplinary problems, it is essential that the requisite computing power be available to manipulate these data sets. Earth scientists are used to a paucity of data, EOS will provide an abundance of data. It is imperative that appropriate statistical and mathematical tools be available for data analysis. Such efforts should also involve modeling of the complex, interrelated global system. The requirement of an multidisciplinary approach suggests that special efforts be made to develop the requisite intellectual tools and cooperative mechanisms in order to answer these problems and overcome disciplinary restrictions.

The last category deals with mission planning and uplink activities. EOS is envisaged as a flexible observational system, capable of receiving new instructions and instrument commands on a regularly scheduled basis. As noted, the sensors should be commandable, capable of sending down only requisite portions of the collected data. They should also be sufficiently flexible to acquire data at a particular gain or offset, to automatically set these parameters based on the signal received, or to acquire data only in particular channels and

at particular data rates. Given the number of instruments which might be co-located on a single platform and their proposed flexibility in command states, a central question becomes one of managing the mission planning and uplink strategy. To facilitate these activities, considerable attention should be given to that part of a data system that allows a researcher to make requests based on results of recently completed scientific analyses. Although individual control of instruments is a possibility, the strength of EOS observations lies in *coordinated* data acquisition. Thus, the area of mission planning is a crucial one.

AUTOMATED DATA COLLECTION AND LOCATION SYSTEM (ADCLS)

The electromagnetic radiation that can be sensed from a satellite in both active and passive systems is severely limited in its ability to penetrate materials at the Earth's surface. As many of the processes to be studied have a strong vertical as well as horizontal component, it will be necessary to obtain information on processes occurring below the effective sampling depth of the satellite or happening on a smaller spatial scale than is readily perceptible from orbit. For example, exchange of deep and surface waters in the ocean is extremely important in nutrient cycling. Several processes below the forest canopy or the soil surface are important in the hydrologic and biogeochemical cycles. An ADCLS would service and connect a suite of *in situ* instruments (e.g., current meters and fluorometers for oceanography, soil moisture detectors for hydrology) that would both relay information through a satellite and receive commands from a ground station. As some of the *in situ* sensors will be freely moving [e.g., drifting buoys in the ocean (see Figure 8), balloons in the atmosphere], it will also be necessary to have a locating system. The required accuracy of the locating system will probably vary from instrument to instrument, but it should range from one meter for instruments frozen into ice sheets to one kilometer for drifting buoys.

An ADCLS will have the advantage of being able to aggregate global *in situ* data for processing and easy access to users. This will allow easy access to consistent processing of data that have been acquired in a distributed fashion. The presence of a command link to the *in situ* sensors will permit some flexibility in sampling.

In addition to observing processes that cannot be measured from satellites, an ADCLS would also be useful in validating the observations of the various remote sensors. Because one of the primary roles of this system is the monitoring of dynamic processes over long time periods, it is essential that the satellite sensors be verified so as to eliminate instrument variations from the time series. Thus, a continuous time series of ground data is required. The ADCLS, by virtue of its rapid data collection and uniform processing, will help provide this information. Similarly, such a system would aid in the

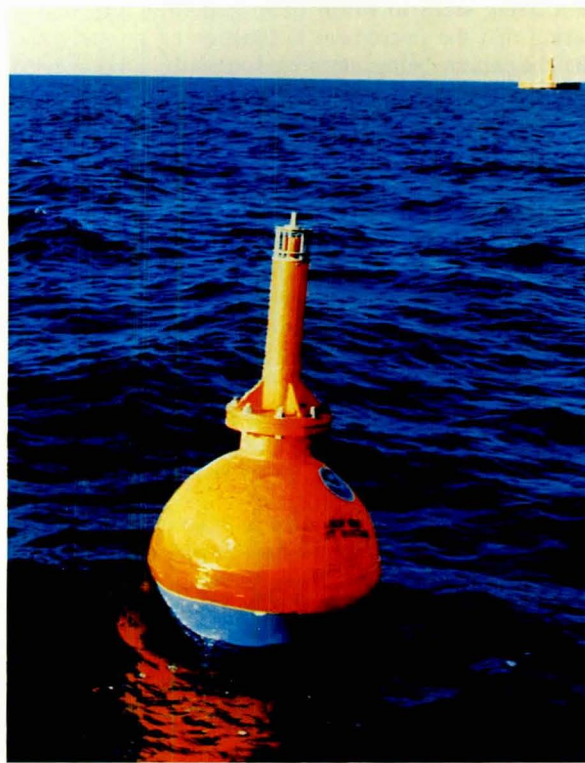


Figure 8. Ocean buoy used with Automatic Data Collection and Location System.

development or modification of the various satellite sensors.

The need for *in situ* data taken in an automated manner is widespread in the Earth sciences. For this reason, the ADCLS can be considered as an element of EOS by itself or in concert with any one of the packages which are described in the following sections.

SURFACE IMAGING AND SOUNDING PACKAGE (SISP)

This section describes a set of satellite instruments that, by the nature of the scientific questions they address, are considered as one package. Combining these instruments to obtain simultaneous, coincident observations provides a considerable enhancement in their usefulness and power to address Earth science needs. These instruments include moderate and high-spatial resolution imaging spectrometers, a multifrequency microwave radiometer, and a lidar atmospheric sounder and altimeter. Although some of these instruments use proven technology, others are still in the engineering design phase. However, it is felt that all of them can be flight-ready during the 1990s.

This package combines several aspects of the Earth-observing approach outlined in the second chapter. That is, it will include measurements of both quasi-static and dynamic quantities, it will have both systematic global and detailed local coverage, it will have the potential for upgrading of observational capability, and it will test new instrument concepts.

The focus of this package is the investigation of the Earth's surface and its interactions with the atmosphere. Some observations of this class have been made and are continuing to be made, but improvements to these measurements are essential if we are to understand the functioning of the biosphere and related physical and chemical processes. In particular, the understanding of biogeochemical cycles, the hydrologic cycle, and the world climate will require such new measurements. These new data sets will be used both to obtain baseline data on these processes and for predictive modeling. The individual instruments within SISP will be used for a number of measurements of interest to several Earth science disciplines. The combination of these data sets will allow an interdisciplinary investigation of interrelated global problems.

Biological systems are highly dynamic and diverse and vary on temporal and spatial scales spanning many orders of magnitude. Deciphering such variability is a major research concern and is greatly aided by repetitive, synoptic data such as those provided by satellite imagery. SISP offers a dramatic advance in the examination of biological systems because of its excellent spatial, temporal, and spectral resolution. The possibilities of recognizing on a global scale individual species or functional groups of organisms and the complex patterns typical of ecosystems will profoundly change ecological study.

The Instruments

(1) Moderate-Resolution Imaging Spectrometer (MODIS)

Visible and infrared images of the surface of the Earth at 1 km spatial resolution have been shown to be particularly useful in characterizing biological and physical processes. To date this work has used the data from the Coastal Zone Color Scanner (CZCS) and from the Advanced Very High Resolution Radiometer (AVHRR). Figures 9 and 10 show examples of the images which can be obtained. In the coastal ocean, significant variations in biological activity generally do not occur on spatial scales less than 1 km (4 km in the open ocean). Over land, there are variations at spatial scales as fine as 10 m which may be significant, but it is not feasible to obtain frequent global coverage at such fine resolution. Viewing land biological systems at the 1 km resolution provides meaningful information on type, extent, and state of biological activity while permitting repeated observations as frequent as every two days with a data rate that is large but not overwhelming. The thermal properties

of the surface are also adequately revealed at this spatial scale. Thus, the 1 km spatial resolution is generally appropriate for a comprehensive view of global biological activity and thermal states through visible and infrared images. (However, 4 km x 4 km is adequate for the open ocean.) MODIS should be designed to address this need with 1 km x 1 km pixels and a swath width to assure complete coverage at the equator at least every two days.

To date, visible and infrared images have been obtained in specific spectral bands chosen in the design of the instrument to provide useful data for a particular area of study. New technology is becoming available which will permit images to be obtained in a spectrometer mode with continuous spectral information over a range of wavelengths divided into a large number of discrete spectral intervals. This wealth of spectral information offers the hope of vastly improved data interpretation, including improved discrimination of specific species and such physiological parameters as the degree of senescence of the biological population being observed. We envision MODIS as incorporating this new technology and providing over 100 spectral bands between 4 and 2.5 μm with resolutions of between 10 and 30 nm. MODIS would also provide spectral images in the 3-5 μm and 8-14 μm atmospheric windows with spectral resolutions of 50 nm and 500 nm, respectively.

The MODIS will measure variations in atmospheric absorption and scattering by aerosols and gases which are of interest in atmospheric studies. These effects will need to be removed from the images in order to obtain quantitative data on surface conditions. The increase in spectral information may be of considerable help in defining these effects and correcting for them.

Data rates as high as 18 megabits per second can be produced by such an instrument. Such a data rate on a continuous basis suggests that a certain amount of data compression may be desirable for routine collection of long-term data sets. With flexibility in the selection of the spectral intervals to transmit to the ground and the ability to combine wavelength intervals into larger bands, this process of compression can be based upon the actual experience gained in analyzing the data, and can be varied according to the region being observed. Data can be grouped to match historically available spectral intervals in order to achieve continuity in these data records. In general, perhaps only 20 spectral bands in the visible and near-infrared might be required, but with new technology, there is hope that the dilemma of choosing specific band parameters in advance of taking data will no longer be necessary.

(2) High-Resolution Imaging Spectrometer (HIRIS)

There is a need for a more detailed coverage on a local basis for land and inland water surfaces. Such high-spatial-resolution images would provide coverage nested within the more extensive observations of the MODIS. The need for such high spatial resolution in ecosystem

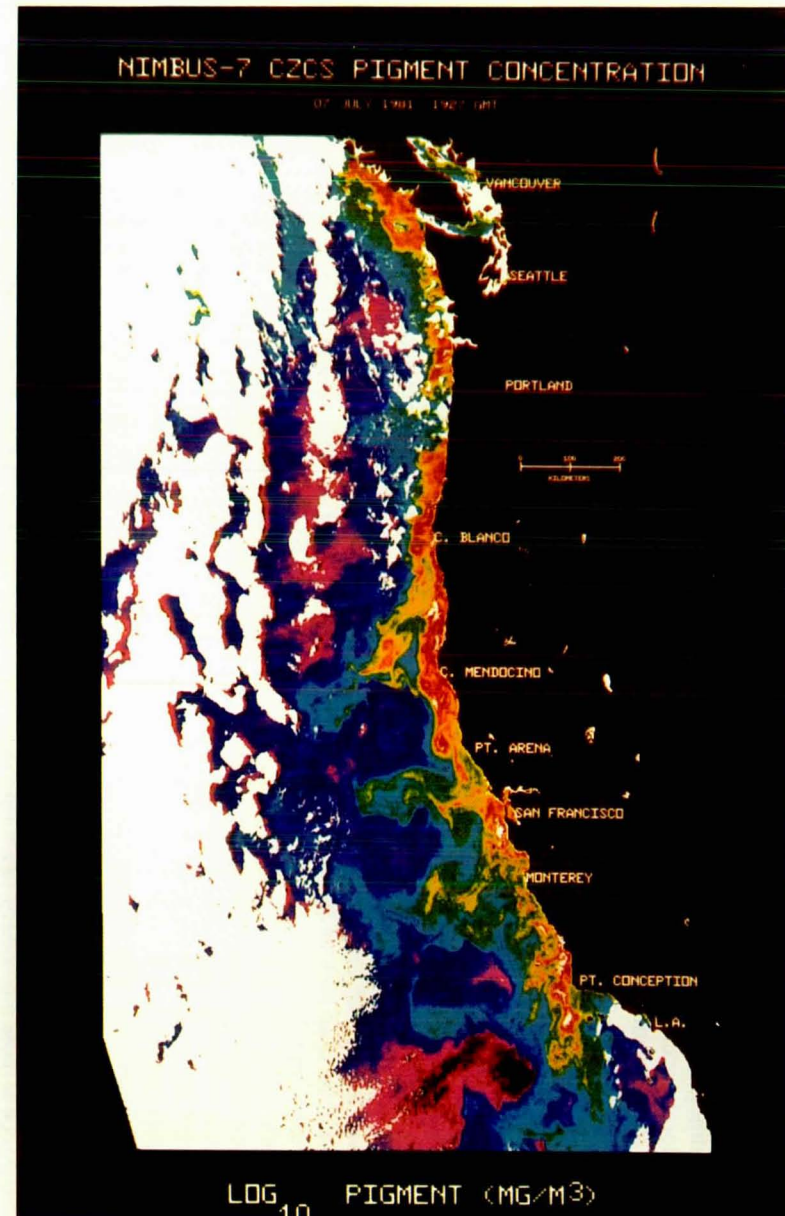
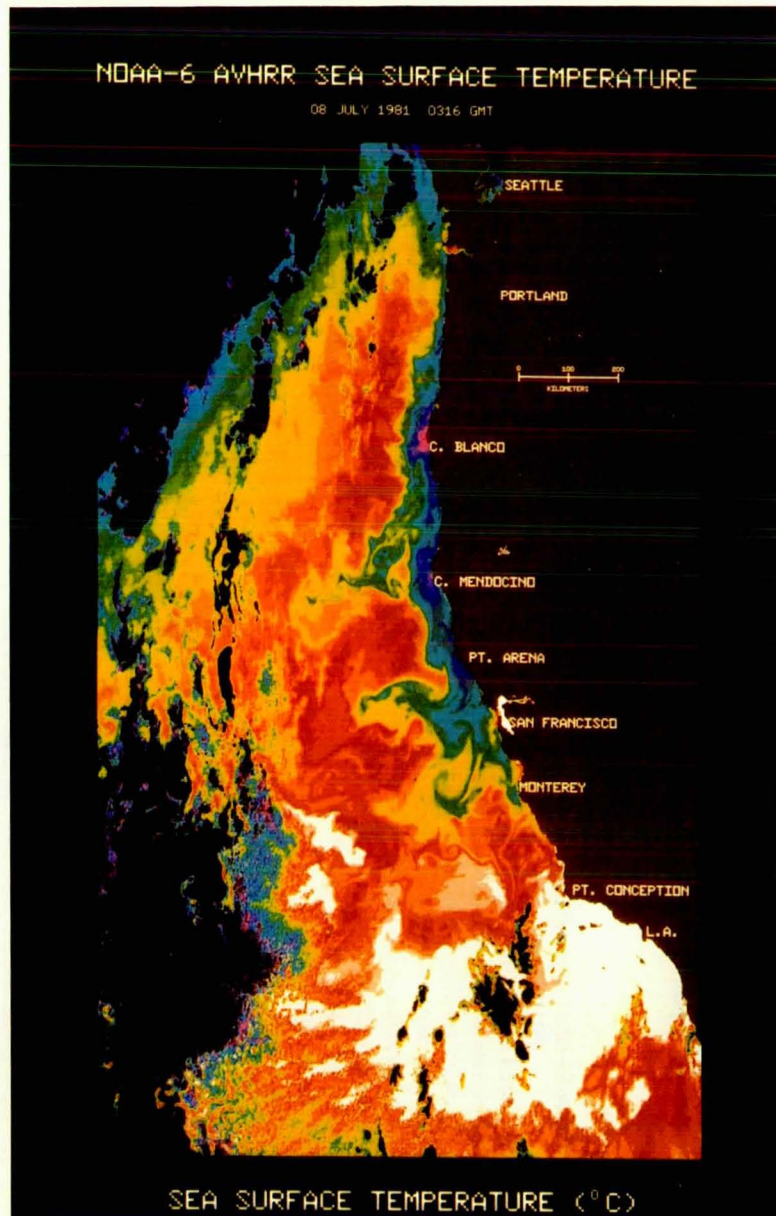


Figure 9. Satellite images of near-surface phytoplankton concentrations and sea surface temperature along the west coast of North America. The white areas (and some black areas in the temperature image) are clouds. This region is part of the California Current System, a productive, southward-moving current.

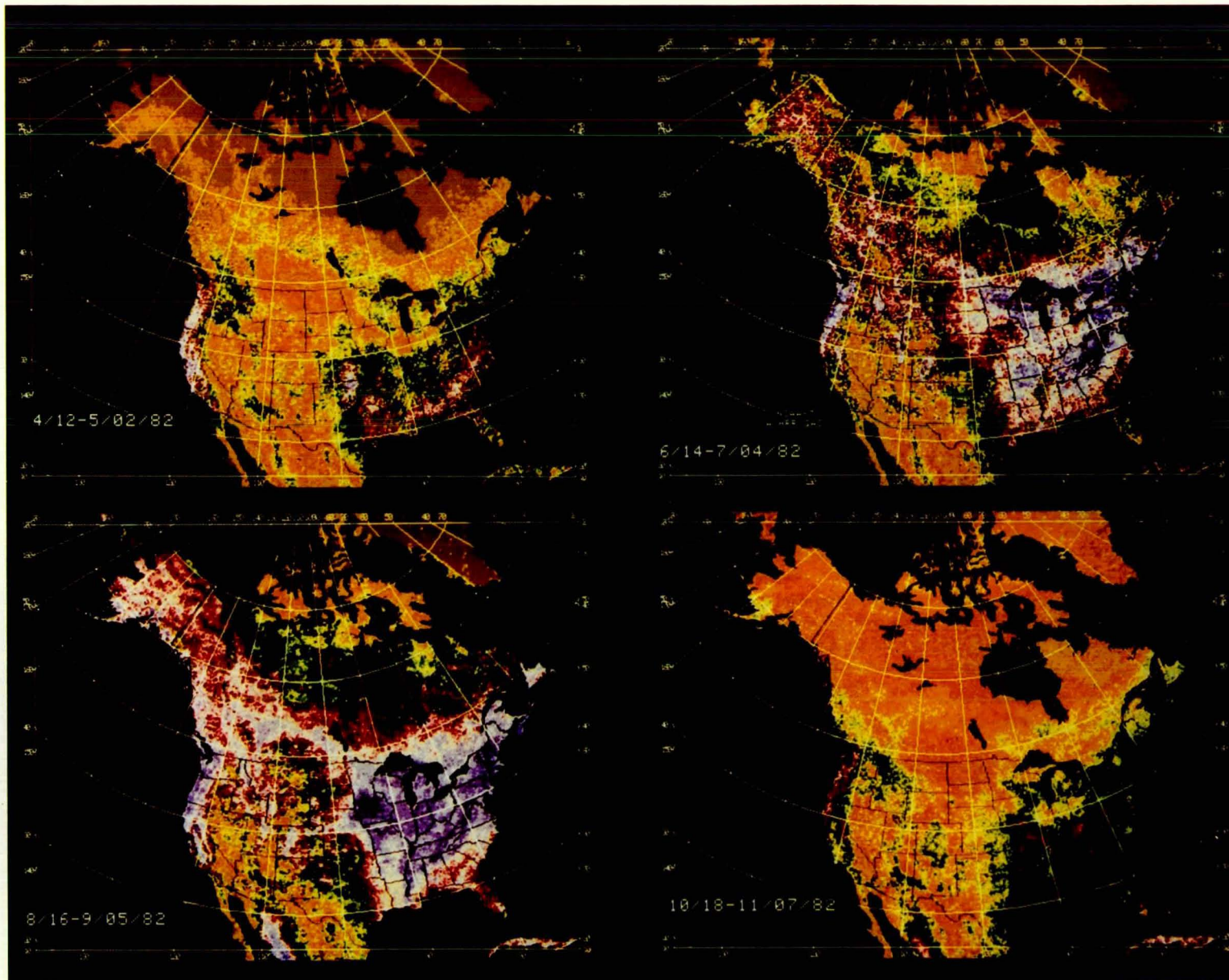


Figure 10. The seasonal variation of the green leaf biomass of North America as observed by the AVHRR from NOAA-7 for four dates in 1982. The purple colors represent the highest values, reds are the next highest, greens represent medium amounts, and the tan and brown colors represent no green leaf biomass. Note the seasonal progression of the development of green leaf biomass which peaks in August and early September. Each image is a composite formed from 21 days of imaging.



Figure 11. Konza Prairie at Manhattan, Kansas. It represents the last of the tall grass prairies in North America. This grassland has never been cultivated and has been designated by NSF as a long-term ecological research site.

characterization is easy to understand by considering the variations in the undisturbed grassland shown in Figure 11 or the variations in the Smoky Mountains forest in Figure 12.

HIRIS will be used for specialized investigations measuring visible and infrared radiance similar to the moderate-resolution sensor. However, it will have a number of significant differences: (1) pixel width will be only about 30 m, (2) spectral resolution will be 10 nm in the visible and near-IR range but similar at thermal IR wavelengths, (3) the swath width will be about 50 km, (4) it will have the ability to point off nadir, and (5) it will be commandable to change its pointing and observing modes.

The usefulness of such a flexible, high-resolution device lies in both its high spatial and spectral resolutions. For example, such high resolution is necessary to develop small-scale maps of surface geologic features, soil types, and continental rock units. As these observables change slowly in time, global maps can be developed over a long time period. High spatial and spectral resolutions also work together to provide detection of

changes in the boundaries of different ecosystems. High resolution will also be useful in studying small-scale processes, such as inland aquatic environments or slash-and-burn agriculture where the relevant spatial scales are often smaller than 1 km. Specialized studies, such as observations of particular agricultural fields for stress, will also benefit from high-resolution observations. Both of these studies will be enhanced by the relatively high revisit capability of this sensor (approximately 2 days in six) as a result of its off-nadir pointing ability. This will be a significant improvement over sampling possible from the thematic mapper, particularly when the effects of clouds on revisit rate are included in the comparison. However, the frequent observations of a particular site are achieved at the sacrifice of observations of other sites in a region. Thus, this sensor will complement rather than supplant the operational style of coverage of the Landsat Thematic Mapper.

The use of a flexible sampling instrument requires careful planning so that scheduling and data processing are handled in an orderly manner. The potentially high data rates of this instrument alone could conceivably

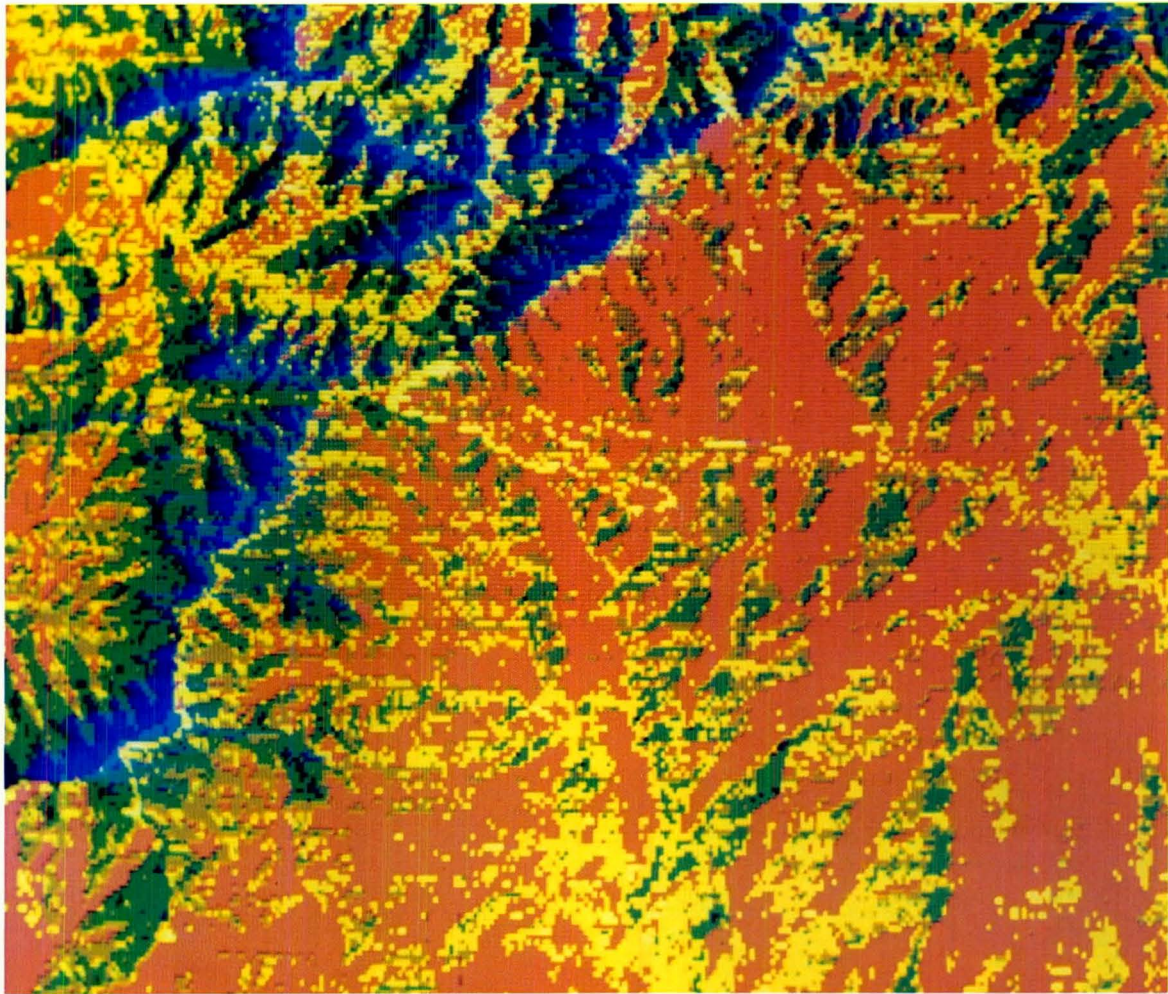


Figure 12. The reflectance ratios from the Landsat multichannel images are the source of this image for a portion of the Smoky Mountains National Park, Tennessee. The image was made from ratios of channels 7 to 5 of a Landsat data tape for the area. The data were color coded: yellow, barren or low-density vegetation; salmon, dense, second-growth deciduous hardwood forest; green, pine forest; and blue-green and blue, spruce fir forests of the high ridges. The yellow strip zigzagging across the center is the road from Newfound Gap on the high ridge descending into the hardwood forests of North Carolina to the east (right). (Courtesy of Soil Carbon Project, Univ. of Calif., Oak Ridge Nat. Lab., P. Zinke).

overwhelm currently projected data processing capabilities. Conflicts over where to point the sensor and when to turn it on are inevitable. However, such problems are not without precedent; large telescopes often have conflicting demands, and other satellite sensors have potentially high data rates. These problems are surmountable, but it will be necessary to have a proper management scheme in place before launch.

(3) High-resolution, Multifrequency Microwave Radiometer (HMMR)

Despite the broad range of capabilities both dem-

onstrated and proposed for visible and infrared imagery, there are several processes, particularly connected to water, which are observable only in the microwave spectral region. Examples include ice characterization (see Figure 13), snow properties, and surface soil moisture. Furthermore, clouds block surface observations in the visible and infrared, but not in the microwave range. Since some regions of the Earth's surface are cloud-covered much of the time, this all-weather viewing capability is advantageous. The HMMR is desired to complement the spatial scale and frequency of coverage of

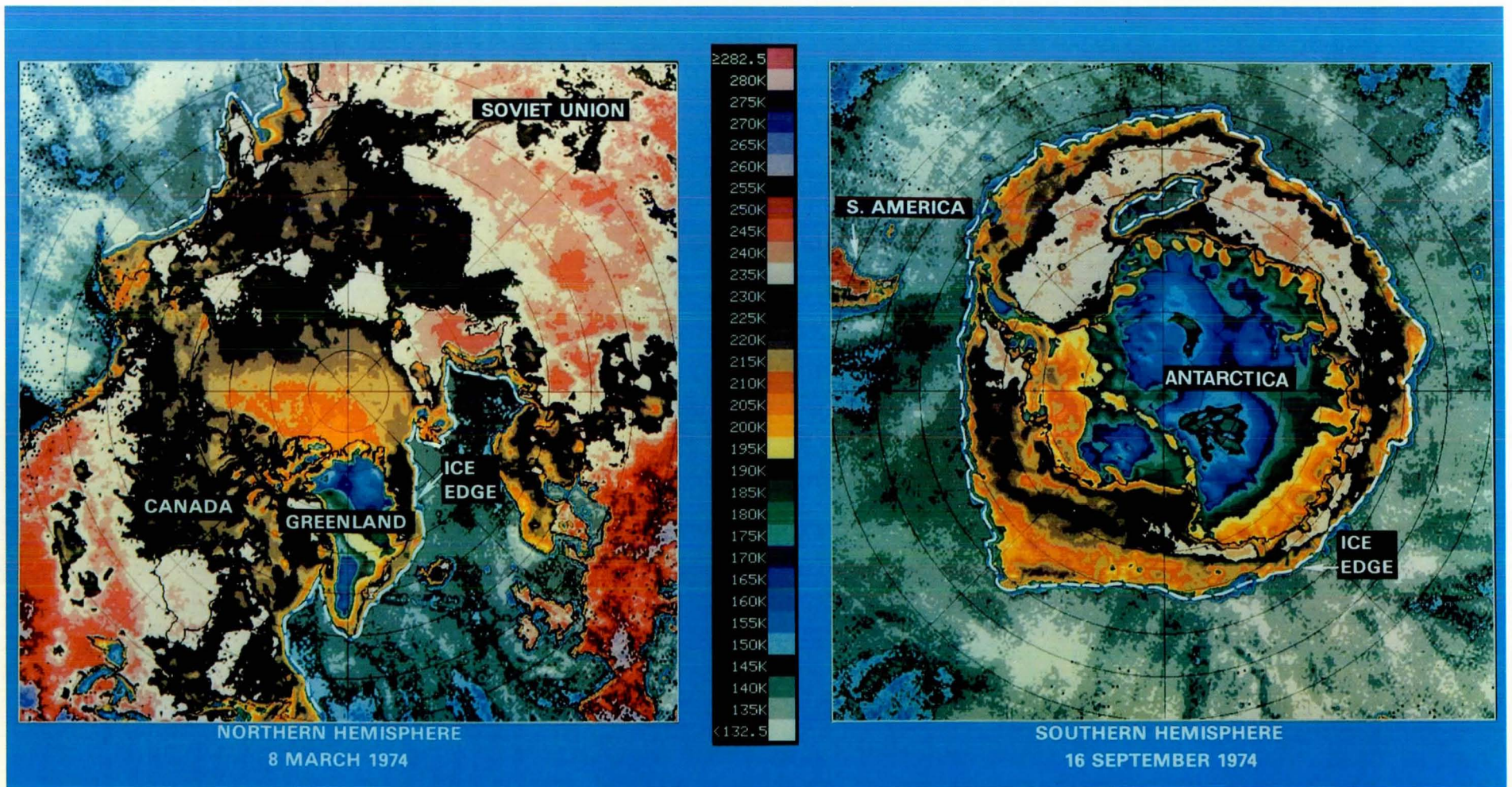


Figure 13. Wintertime images of the northern and southern hemispheres from the Electrically Scanning Microwave Radiometer (ESMR) on board the Nimbus 5 satellite. The sharp contrast between microwave emission from sea ice and those from open water allows ready determination of the sea ice edge (dashed white line) from these images.

MODIS with passive microwave observations. Thus, pixel sizes down to 1 km x 1 km are desirable with a swath width of 1500 km to provide global coverage every two days. We recognize that practical limits on antenna size may prohibit obtaining spatial resolutions comparable to MODIS, particularly at the lower end of this frequency range. A resolution of 2.5 km at 36.5 GHz is representative of the resolution which we feel is still scientifically quite useful and worth pushing technology to obtain.

Microwaves emanating from natural surfaces are affected by the emissivity of the surface and by atmospheric conditions. As both emissivity and atmospheric conditions vary, the variations in microwave radiation sensed at the satellite can be used to infer both surface and atmospheric conditions. For example, the emissivity of the ocean will vary according to the structure of capillary waves which depend on processes such as wind and rainfall rate. Similarly, temperature, type, and melt condition of ice affect its emissivity. The amount of water in the atmosphere including precipitation will affect the amount of microwave radiation penetrating from the surface to the satellite. As with the imaging spectrometers, these processes will vary in their effects at different wavelengths.

The temporal and spatial resolution of these measurements is dictated by the dynamics of the observed variables and by the requirement to maintain a manageable data rate. That is, lower resolution may seriously undersample variable processes, and higher resolution may overwhelm the data analysis and interpretation system.

(4) Lidar Atmospheric Sounder and Altimeter (LASA)

The lidar discussed in this section is directed toward a series of composition measurements. It will operate in the visible and near infrared and include measurements of the altitude distributions of water vapor, aerosols, thin clouds, and dust. The inclusion of this particular instrument in the same package as the imaging spectrometers is driven by the desire to use the atmospheric backscatter measured by the lidar to help correct surface image data. However, the prime mission envisioned for LASA is to determine the distribution of water vapor on the horizontal and vertical scales required to understand the atmospheric branch of the hydrological cycle.

The distribution of atmospheric water vapor is a spatial continuum with all scales of the dynamic atmosphere represented. It is possible to consider the major problems of continental transport, weather systems variation, and large-scale systems on scales of 10 to 100 km. Within this scale size the altitude resolution, of the order of one kilometer, is desirable and cannot be achieved with passive techniques.

The role of the LASA in the determination of aerosols and particulate matter is classical and will be one of the significant scientific questions addressed with this data base. The very aerosols and thin clouds that are of interest

to the atmospheric sciences community are required by the surface water and land communities to interpret ground images. There are obvious questions that will remain even when the aerosol backscattering and absorption are measured, however, it will be possible to extend the backscatter measurements with models for the aerosol phase functions and accurately correct the surface image data.

LASA offers the potential to perform distance measurements over a wide baseline. The objective for solid earth geophysics is to measure both motion and deformation of the lithospheric plates, which on an annual basis varies from less than a millimeter to centimeters. Spacecraft distance measurements could potentially be carried out by the LASA altimeter with ranging to a fixed array of corner reflectors. In simplest terms, the requirement is to measure the secular change in the distance vector between two (or more) points on the surface of the earth to centimeter-scale accuracy. This type of measurement could also improve estimates of spacecraft location and altitude. By measuring the return time of the signal, it is possible to use LASA as an altimeter. However, multiple scattering from the surface can occur, so it is necessary to view the same spot at several look angles to obtain an unambiguous altimetric measurement. Such repeated sampling is possible over topography such as land and ice which are only slowly changing in time. As research with a lidar sounder progresses, it may be possible to obtain temperature profiles as well as some constituents of the atmosphere (e.g. SO₂ and NO₂) with high vertical resolution.

Orbit Considerations

The science of this package focuses on imaging the surface to determine its physical and biological state. The orbit choice for this payload is sun-synchronous with an equator crossing time of 2:00 p.m. The choice of sun-synchronous orbit is made for two reasons. First, global coverage is desired particularly when the full multidisciplinary requirements are considered. Once one decides to obtain nearly global coverage, the available orbits for efficient remote sensing are either sun-synchronous or have slow rates of orbit precession which result in only gradual changes in the local times being observed. These changes are slow enough to be nearly in phase with seasonal or annual cycles and therefore combine the effects of diurnal cycles with seasonal and annual cycles. This greatly confounds the data interpretation task. Second, sun-synchronous orbits offer consistent illumination conditions for optical and near-IR measurements and two fixed observations within the diurnal cycle. Both of these properties simplify data analysis and the building of long-term measurement series. The 2:00 p.m. crossing time has been chosen for several reasons. It is close enough to local noon to permit good illumination in the visible and near-IR for passive

observations, but far enough away from noon to avoid substantial problems with sun glint from water surfaces. Further, the day/night contrast between 2 00 a m and 2 00 p m is thought to be the most revealing of thermal and moisture stress in soils and vegetation. This time is coincident with the afternoon orbit of the operational NOAA satellite series which can therefore provide coincident, ancillary meteorological data. The afternoon time is also desirable as a contrast to LANDSAT observations being made at 10 00 a m local times.

The other aspects of orbit selection are the altitude and eccentricity. The requirements on the MODIS, HMMR, and LASA are for global coverage of the earth every two days at both day and night times. This ties the choice of orbit altitude to the swath width achievable by the instrument. Based on past experience, an altitude between 600 and 1,000 km should be capable of satisfying this need. Non-circular orbits offer a variety of interesting possibilities, but they do not provide a basis for consistent daily coverage of the Earth at similar spatial resolution. Given the high priority assigned to obtaining climatological-style data sets for the accomplishment of the science tasks identified in this report, a circular orbit is necessary. Complementary research missions which capitalize on the variety of observations possible from eccentric, non-sun-synchronous orbits are certainly desirable, but these are not of highest priority for the EOS in view of its emphasis on serving much of the multidisciplinary and interdisciplinary needs of Earth science on a sustained basis.

Justification of Package

Each instrument in this package will be useful in solving several problems specific to individual Earth science disciplines. The two imaging spectrometers will be used to collect data on processes occurring at the Earth's surface. Within the geological sciences, such data will be useful for mapping of surface rock and soil characteristics. In the land-based life sciences spectral measurements will be used to determine some of the energy and water balance components, to characterize vegetation type and health, and to measure land use changes. These spectral data will be used to characterize several flux components of the hydrologic cycle as well as observe the variability of these fluxes. Such observations will also be used to characterize sea ice and define its limits of variability. The distribution and growth rate of phytoplankton biomass of both inland aquatic and oceanic systems will be studied with these spectral data. In addition, such data can be used to characterize some aspects of mesoscale ocean circulation. Finally, the spectrometers will provide some data on fluxes at the interface between the atmosphere and land or ocean surfaces as well as information on cloud characteristics. Improved measurements of the extent of biological activity on both land and ocean will be a key to improving

quantitative estimates for the global amount of biomass and rate of primary productivity.

The microwave radiometer measurements will play a major role in determining the water and energy balance of the Earth's surface, as well as their relation to the atmosphere. It will provide measurements of key processes of the hydrologic cycle, such as evapotranspiration, water content on and near the land surface, and perhaps some sampling of precipitation for use with geostationary data. These measurements will provide an all-weather capability for describing ice dynamics, variability, and heat fluxes. The microwave data are important for the understanding of the atmospheric role in the cycling of water and heat.

The lidar measurements will provide important information on the vertical and horizontal distribution of atmospheric water vapor, which is a key component of the hydrologic cycle. These lidar measurements of the atmosphere are crucial to the removal of atmospheric effects in the surface imagery from the two spectrometers. Finally, the lidar will be able to make precise altimetric and distance measurements for topographic and solid earth geophysics studies.

The solution of several more general interdisciplinary problems requires that this package of instruments fly together. As an example, the measurement of atmospheric water vapor, precipitation, soil moisture, snow cover, and evapotranspiration is required in order to quantify fluxes in the global hydrologic cycle. This package will greatly improve our knowledge of all of these quantities with the exception of precipitation. The highly variable nature of precipitation rate is incompatible with the sampling frequency obtainable in low Earth orbit. For soil moisture, the HMMR is necessary to measure the upper-layer water content under conditions of bare soil to moderate vegetation cover. When heavy vegetation cover is present, canopy temperatures from MODIS must be employed to estimate the soil moisture. At the same time, HIRIS can be employed to specify biomass and vegetation structure, indicating when a switch must be made from microwave to thermal infrared determinations of soil moisture. Connected with this is the determination of evaporative flux, which requires the microwave soil moisture value, the thermal infrared surface temperature, HIRIS vegetation structure, and a MODIS albedo determination. In all these areas, land cover images from MODIS or HIRIS are necessary depending on the scale of application. The HMMR and MODIS will provide an indication of evaporation from the oceans by determining sea surface temperature. The LASA will give the moisture content of the air and map the topography of the globe which plays a crucial role in runoff.

Another example of the synergism of the SISP is in the study of global primary productivity and biomass. Both are crucial to an understanding of the biogeochemical activity. HIRIS coverage nested inside of MODIS images provides similar information over land. These

images can also be used to determine the spatial extent of the different ecosystems. This can then be combined with *in situ* characterization of typical biomass amounts per area in the various ecosystems to obtain an estimate of total land biomass. The HMMR provides complementary measurements of the state of the vegetation and the only data for cloud-covered regions. In this context, the role of LASA is to provide atmospheric corrections to the images.

In addition to the necessity of having all the instruments available as a package so that the appropriate capability will be available for coincident measurements, there is also the consideration of data processing requirements. Although merging the data from independently flying instruments is manageable, integrated interpretation of these data is greatly facilitated if they are all acquired at the same time. Finally, flying the instruments on a common platform also facilitates the servicing function. All the instruments can be serviced with one trip rather than many.

MEASUREMENT STRATEGY FOR SENSING WITH ACTIVE MICROWAVES (SAM)

This section describes a set of satellite measurements that share commonality in instrument type—active microwave—and the need for a high-inclination, near-polar orbit. These instruments are collectively called the SAM package (for Sensing with Active Microwaves) and are (1) a synthetic aperture imaging radar (SAR), (2) a radar altimeter (ALT), and (3) a radar scatterometer (SCAT). All of these instruments are highly developed, although the multiple-look angle, multiple-frequency imaging radar has yet to be implemented.

A high-inclination SAM mission will meet a number of scientific objectives in geology, agriculture, forestry, land cover, dynamic oceanography, and the cryospheric sciences. The most demanding instrument in this group is the SAR in terms of power, weight, cost, data rate, and complexity. The ALT, SCAT, and SAR form a synergistic scientific instrument package for ocean and ice applications. The radar altimeter, depending on the choice of frequency, could also be used for measuring land topography, although laser or stereogrammetric imaging techniques are expected to provide significantly better resolution.

The SAM instrument grouping exemplifies the interactive and synergistic aspects of the EOS concept: global and local coverage of dynamic and quasi-static phenomena, and a major step in observational and instrumentation capabilities.

The Instruments

(1) Synthetic Aperture Radar (SAR)

Application of SAR techniques to the Earth sciences

addresses a wide variety of questions because a high-resolution, all-weather image is available, surface features can be highlighted by choice of illumination angles, and the microwave albedo is often diagnostic of important physical properties such as moisture content and roughness. Just as HMMR will provide an all-weather microwave complement to MODIS, SAR offers a microwave complement to HIRIS with similar spatial resolution and targeted observations.

For sea ice applications, SAR is an identification and location tool for a number of ice features such as ridges, floes, and leads; it can result in a data set from which ice motion and deformation can be extracted. Additionally, the radar albedo of ice can provide relative information on the age and stress state of sea ice. Inland, SAR can map surface features such as nunataks, crevasses, and flow lines to supplement other observations.

In viewing vegetative land cover, the highest priority applications of SAR are the characterization, areal extent determination, and condition assessment of vegetation and changes in these phenomena. Other pertinent uses are (1) soil moisture observation, (2) area estimation for wet land and other ecosystems, and (3) general assessment of the surface hydrologic environment. An illustration of what can be observed using this technology is given in Figure 14.

In geology, key investigations center on geologic mapping and stereo imaging. Geologic interpretation of radar imagery is based on the analysis of image recognition elements which include tone, texture, shape, pattern, and context. SAR has shown the most utility for structural mapping of all remote sensing devices. SAR also has a demonstrated capability to penetrate sand and alluvium to a depth of 2 to 4 meters in arid regions, thereby permitting subsurface mapping.

Over the ocean, SAR is sensitive to short wavelength surface waves (gravity-capillary wavelets). The oceanographic phenomena measurable in this way are those that influence the structure and distribution of these short waves. Swell, internal waves, surface currents, surface wind speed, rings, oceanic fronts, and bathymetry have all been mapped with SAR.

Among the disciplines discussed above, the scientific application of SAR varies from the experimental to the mature research stage, ranging over a wide spectrum of maturity in interpretation of data for specific phenomena. Thus SAR is both an experimental sensor and a routine research tool.

The instrument requirements of the various research tasks differ, a SAR which meets all of these needs is naturally driven toward the severest constraints posed by each of these individual requirements. A candidate SAR that meets most of the requirements for the entire Earth science community would have the following characteristics (see "Science Requirements for Free-Flying Imaging Radar (FIREX) Experiment," JPL Report, June 1, 1982).

BRAZILIAN FLOODPLAINS

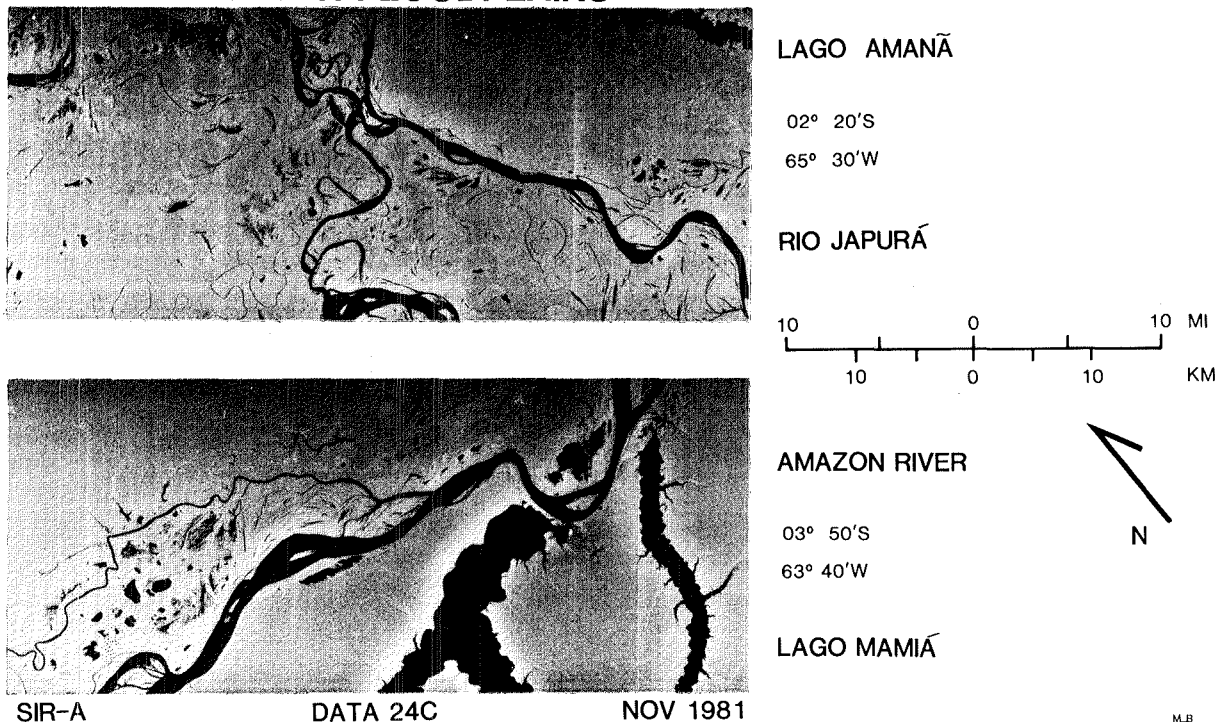


Figure 14. Synthetic-aperture radar imagery of the central Amazon basin. Images were taken from Space Shuttle (SIR-A). The complex geomorphology of the floodplain lakes and river meanders is evident. Further analysis of such imagery should permit discrimination of major habitats and their variation in area as the rivers rise and fall in level. The fertility of floodplains depends on these variations. (Courtesy of L. Bryan, Jet Propulsion Laboratory).

Frequency: Dual, C, and L bands (could also include X band)
Polarization: HH, VV
Effective Look Angle: Low (15 degrees - 20 degrees), Medium (30 degrees - 35 degrees), High (55 degrees - 65 degrees)
Resolution: 30m, 4 looks
Swath Width: 200km
Revisit Time: < 10 days; ~ daily for some ice and ocean applications
Coverage: Near-global
Geometrical Positioning of Image: consistent with the resolution, pixel location exact to within 100 m
(2) Radar Altimeter (ALT) and Radar Scatterometer (SCAT)

Quantitative observations of ocean phenomena mapped by the SAR are provided by ALT and SCAT. Ocean waves and upper ocean currents are forced by the atmospheric wind stress on the surface of the ocean. Many of these oceanic transients have climatic, oceanographic, or utilitarian operational significance which can be assessed only if accurate, global scale forcing data are

available for use in numerical models. These data are not now available from conventional observation and analysis systems. The SAM system, repeatedly mapping and measuring the ocean surface stress and dynamic topography fields, could provide this uniquely valuable forcing data set to the research community. ALT would measure the time-dependent portion of ocean topography from which surface geostrophic currents are derived. Figure 15 illustrates the variability in ocean circulation as observed by Seasat. The actual instrument would be similar in capability to that flown on Seasat (rms precision of the height measurement ~ 10cm for a sea state < 20m). It would require a microwave radiometer for atmospheric moisture corrections. An adaptive tracking feature such as that designed for the NOSS altimeter should be incorporated for precise measurements over ice and land surfaces.

SCAT would measure the vector wind stress field over the oceans. The scatterometer should be similar to the one designed for NOSS and proposed to be flown on the Navy's N-ROSS spacecraft. The specific requirements for the instrument are detailed in the report of the

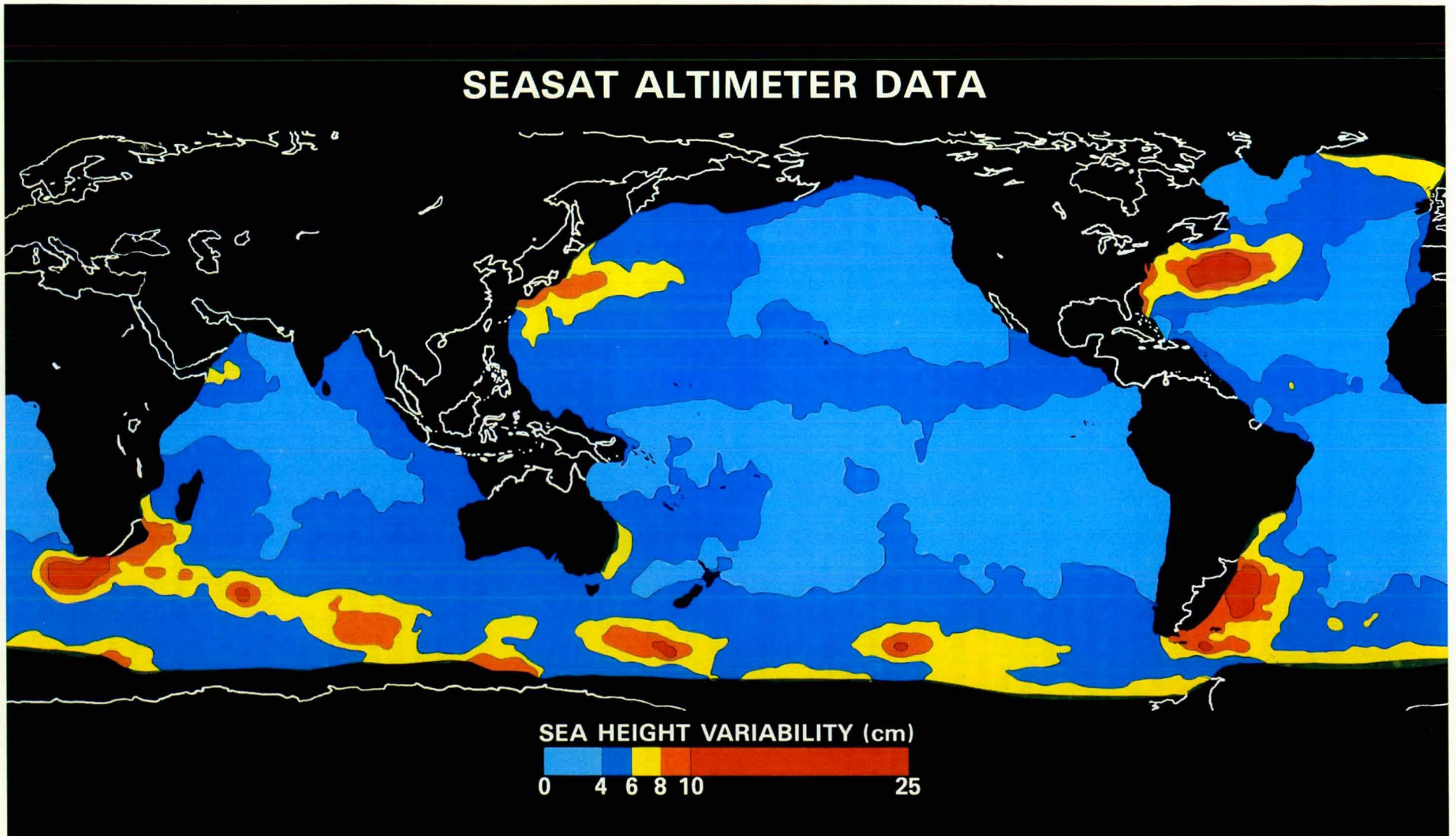


Figure 15. Global mesoscale sea height variability measured by the Seasat altimeter, September 15 to October 10, 1978, when the satellite track repeated at a 3-day interval.

NASA Satellite Surface Stress Working Group

Complete assessment of the topography of ice sheets will require both ALT and a lidar altimeter. Although lidar is not included as part of the SAM instrument group, it is an element of the LASA instrument in SISP. A radar altimeter with Seasat characteristics and limited modifications (i.e., adaptive tracking) operating over ice sheets will adequately monitor changes of ice sheet elevation economically and systematically at a limited number of points over the ice sheets at intervals from two to ten years. Surveys at two-year intervals could provide the data needed to determine mass balance changes of ice shelves. If considerable imbalance is found, lidar altimetry could then be used to determine if any changes of their inland boundary (flotation line) are taking place. Similarly, if unexpected changes of inland ice are detected by radar altimetry or other remote sensing instruments, lidar altimetry will be repeated over relevant regions.

Over sea ice, ALT and SCAT complement information from SAR (and MODIS) on the extent, type, percentage ice cover, and surface state of sea ice. This information should be collected daily in conjunction with the other systems to meet meteorological and oceanographic needs.

Surface Data

Surface verification data on wind speed and direction and *in situ* current measurements need to be continuously collected at certain key locations to calibrate SAM package data. Over sea ice, selected surface monitoring of wind speed and direction is unique information not available from spacecraft instrumentation, and is required to understand the temporal trends in sea ice characteristics. Similarly, temperature data should also be collected over sea ice.

Orbit Considerations

A near-polar orbit is desired to meet ice sensing requirements, but a sun-synchronous orbit offers the ability to image the vegetative environment at the same time of day as sensors in the visible and infrared regions of the spectrum. In such an orbit, depending on the design of the SAR, one of the poles, preferably the north, could be imaged or nearly imaged, and the other pole would be missed by about 7 degrees of latitude. ALT will obviously miss both poles by 7 degrees, but this is not considered a serious limitation.

As previously noted, the most stringent revisit time requirement is daily and is dictated by ocean and ice science requirements on the SAR. However, there is a tradeoff between revisit interval and ground track separation. For example, spatial wavelength sampling considerations for ALT dictate an equatorial ground track separation corresponding to a 14-to-20 day repeat interval. Thus, a compromise revisit interval might be 10

days. For revisit, the ground track needs to be accurately repeated, to within 1 km.

A further orbital constraint is the simultaneous operation of the SAR and SISP instruments for spectral coverage of visible, IR, and microwave wavelengths. Such a mode of operation would enable comprehensive observations of phenomena which change on time scales of the order of hours. Foliage orientation and plant water status are examples of such phenomena. SAR should be implemented in such a way as to enable it to measure, within an hour or so, the same ground locations at low-to-moderate look angles that HIRIS measures near nadir.

Alternative implementations are possible without seriously compromising the science needs addressed by this system. The requirements for high spatial and temporal coincidence between SAR and the SISP package of quasi-nadir looking imagers effectively dictate the choice of the SAR orbit. However, altimeter and scatterometer data are primarily useful for building a global picture of ocean circulation and surface wind features which persist for times greater than 12 hours. This removes any need for these radars to observe the same ground track at the same time as other instruments. Thus, any satellite which can accommodate SCATT requirements for global daily coverage can carry the SCATT component of the SAM package. One possibility is the incorporation of such a scatterometer on future operational ocean-sensing satellites, which might logically be expected to develop from the N-ROSS demonstration mission. Another possibility would be a platform which carried SCATT in addition to the SISP and/or APACM instruments described in the next section of this chapter. The altimeter could also be deployed upon a variety of different platforms provided that its needs for a precisely repeating ground trace and precise determination of the altimeter antenna location in space are met. Thus, the SAM package could be implemented in an integrated or distributed manner.

Summary

The total SAM package addresses major scientific problems in physical oceanography and sea and land ice sciences. The SAR, in conjunction with SISP, provides measurements of the Earth's land mass over the visible, IR, and microwave portions of the electromagnetic spectrum. Thus, highly significant problems in geology, forestry, agriculture, hydrology, and land cover will be addressed as well. Air-sea interaction offers a good example of how the SISP and SAM packages combine to satisfy research requirements. To quantify air-sea boundary processes, measurements are needed of sea surface temperature, sea state, sea surface wind, atmospheric humidity above the ocean, and atmospheric temperature profiles. MODIS and HMMR will determine sea surface temperature. ALT and SCAT provide measurements of sea state and sea surface wind. LASA, and to some

extent HMMR, will measure atmospheric water vapor. Atmospheric temperature will be obtained from operational sounders and perhaps from LASA. Thus, the comprehensive data set is knit together from instruments which serve a variety of other purposes.

ATMOSPHERIC PHYSICAL AND CHEMICAL MONITOR (APACM)

The focus of this package is the chemistry and physics of the atmosphere. Although the atmosphere is currently the most extensively observed portion of the Earth system, a number of additional measurements are needed before the scientific challenge of forecasting the future state of the atmosphere on a wide range of time scales can be more fully met. The atmosphere is the most dynamic of the Earth's environmental regions, significant phenomena occur on time scales varying from minutes to decades. Progress in understanding these phenomena is usually measured in terms of an improved ability to predict the future state of the atmosphere. The new challenges for the 1990s in this area will be to better understand the global patterns of winds, the coupling of the upper and lower portions of the atmosphere, the distribution and ultimate fate of the many minor chemical constituents of the atmosphere, and the response of the atmosphere to modifications in its radiative properties and thermal structure caused by changes in its composition. There are also a number of science questions about the atmosphere which are connected to knowledge of the other regions of the Earth system, such as air-sea exchange of momentum, the exchange of water, other chemical species, and particulates between the atmosphere and the surface, and the evolution and prediction of climate.

This element of EOS provides the global view of the gaseous envelope surrounding the Earth, providing the information required to discern changes in the atmosphere as a complete unit. There are relationships among the data sets supplied by this unit which are obvious to the atmospheric science community, but there are equally important links with the SISP and SAM packages. The surface of Earth contributes many perturbing influences to the atmosphere: it is a source of trace chemicals, a source of viscous stress and waves, and a source of latent heat in the form of water vapor. In exchange, the atmosphere provides sources of chemical perturbation to the land and sea through acidic precipitation and dry deposition, as well as causing wind stress and erosion by rain, snow, and wind. Thus, the links in the Earth system are all closed as are the relationships between the elements of the Earth Observing System.

Observational Needs and Capabilities

Determination of the chemical and thermodynamic state of the atmosphere requires a suite of observations

which are, in general, mutually compatible and would form one of the in-orbit elements of EOS. It is assumed that one of the baseline requirements of this element is the incorporation of the existing "operational" meteorological data set into the Earth sciences data base. It is assumed that by the time of this mission the operational data set will include both spectral and total solar irradiance and terrestrial outgoing radiation. The primary instrumental set contained in this group will consist of those instruments required to detect the chemical and dynamic state of the atmosphere from the ground through the exobase. The instrument complement divides naturally into four related groups: These are tropospheric chemical composition monitors, tropospheric active wind sensors, upper atmosphere chemical state monitors, and upper atmosphere wind sensors.

In general, the troposphere and upper atmosphere are coupled on time scales which are sufficiently long to permit the observations of the two regions to be obtained independently. If this is done, some overlap of observations about the tropopause facilitates their integration as a data set. In the troposphere, the transport of trace chemicals is determined by the wind field, but there is no meaningful feedback of the chemistry and chemical composition into the dynamics on the spatial and temporal scales of the possible measurements. Thus, the measurement of the dynamic state need not include considerations of tropospheric chemistry. From low Earth orbit, the spread of tropospheric trace species from a highly localized source during a single day cannot be observed because a given area is only viewed twice a day. The component of the observed distribution of trace constituents which is due to the wind fields must be determined by using models to interpolate the global wind field over the day from the measurements. Therefore, the tropospheric chemical and dynamic measurements may be made independently. In the upper atmosphere, the dynamics and chemistry are believed to be strongly coupled so that their individual measurements need to be coordinated, as in the plan for the Upper Atmosphere Research Satellite (UARS).

The direct observation of the dynamic state of the atmosphere requires the measurement of the Doppler shift in wavelength of some signal which the atmosphere either emits naturally or which can be produced by laser illumination. In the upper atmosphere, techniques are being developed to do this as a part of UARS. These techniques use natural emission features of oxygen and achieve desired vertical resolution by scanning the limb of the Earth with the instrument designed to view only a narrow altitude band. In the lower atmosphere, the increased pressure of the atmosphere broadens these features, obscuring the doppler shifts in specific spectral lines, and viewing the limb becomes impractical due to the ubiquitous presence of at least some obscuring clouds or haze over any long horizontal path through the troposphere. This dictates that the sensor employ active tech-

niques and look down through the atmosphere. At present, Doppler lidar using one of several different wavelengths appears to be the only hope for obtaining this measurement.

The trace chemical species of the atmosphere are of interest even when their compositions are only tens of parts per trillion. This presents a formidable challenge even to *in situ* measurements in the laboratory. However, satellite observations of many gases are possible. Figure 16 shows an example of data from NIMBUS 7 for HNO_3 .

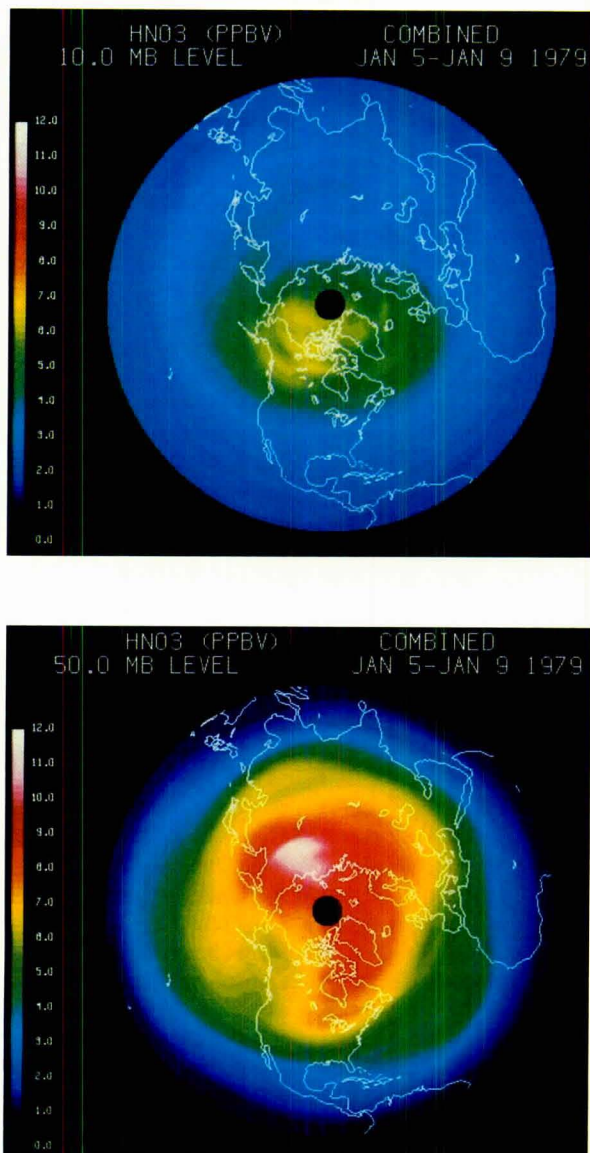


Figure 16. Nitric acid variation in the northern hemisphere of the stratosphere at the 10 and 50 mb levels as observed by LIMS.

The key to making these measurements remotely is to capitalize on the natural spectral features of the specific chemical to be observed. If a trace constituent has a spectral feature which is very strong in comparison to the background features of the other atmospheric gases, it can be detected even in small concentrations. Thus, chemical species measurements rely on unique, individual characteristics of the gases being measured. This in turn implies making use of different instruments which operate in spectral regions ranging from the ultraviolet to the microwave. The application of these instruments to the upper and lower atmosphere is governed by the same considerations as were discussed for wind sensing. Namely, in the upper atmosphere where the atmosphere is generally free from clouds and haze, limb viewing provides good vertical resolution of composition profiles. In the lower atmosphere, only nadir viewing will be successful in seeing to the ground. If natural emissions of an atmospheric gas are being used to make a down-looking measurement, some characteristic of the emission or a set of different emissions must be used to obtain information on the vertical distribution of the constituent. The vertical resolution which can be achieved in this way is generally quite coarse; often only two vertical levels can be independently determined in the troposphere. Where this is not adequate, active lidar-based techniques currently offer the only hope of obtaining improved altitude resolution. Even these techniques are currently thought to be inadequate for detecting some species, and a combination of modeling and *in situ* observations will always be required to infer some components of the detailed atmospheric composition.

The following sections discuss each group of potential measurement devices in more detail. The instruments are generally candidate examples and not necessarily the only solution to the measurement need. The flight of UARS and of several Shuttle instruments which measure atmospheric composition will greatly improve our knowledge of exactly which observations are truly needed on a long-term basis and which techniques are the most appropriate for making the measurements. This certainly is one example of why EOS should logically follow certain planned missions and should be capable of evolving during a sustained period of operation.

The Instruments

(1) Tropospheric Composition Monitors

The space-based measurement of tropospheric chemicals focuses on those important substances which have significant spatial variation so that a few ground-based measurements are not adequate to characterize the global distribution. This excludes those chemicals with very long tropospheric lifetimes. On the other hand, substances with very short lifetimes will, in general, not be present in sufficiently large concentrations to be observable remotely. As discussed earlier, those chemical

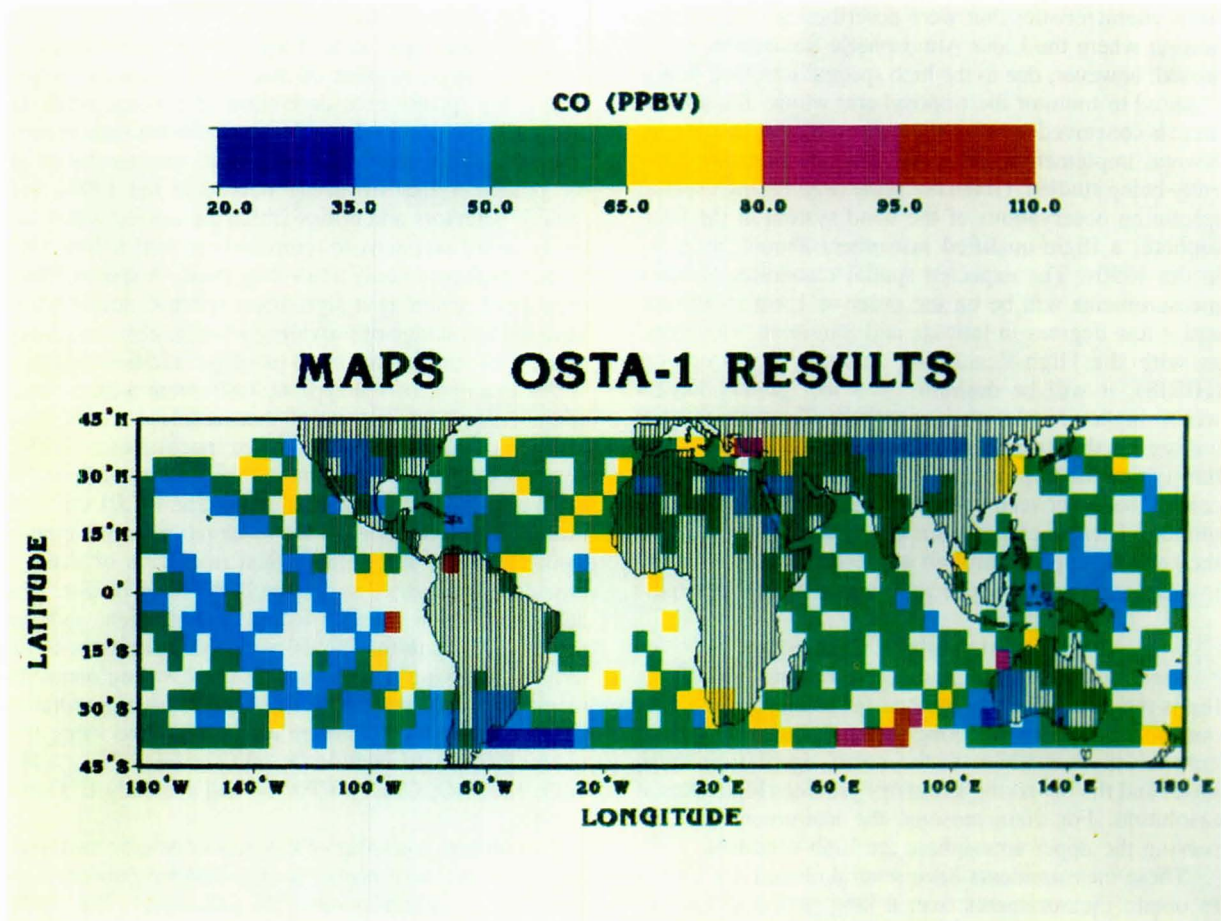


Figure 17. Preliminary results of the Measurement of Air Pollution from Satellites (MAPS) experiment as flown as part of the OSTA-1 payload on the STS-2 mission during early November 1981. The data represent the average value of the carbon monoxide mixing ratio in the middle to upper troposphere (between 6 and 12 km).

species which can be observed will be measured by exploiting unique spectral features of the molecule. In the near term, where possible, this will be done passively. Measurements of total column content of CO have already been obtained using a correlation radiometer (see Figure 17). This technique can be extended to NH₃ and perhaps to other species as well. Other passive techniques, such as interferometers and spectrometers of various wavelengths, can also be exploited to measure more constituents. Where passive techniques are inadequate or there is a requirement for profile information, lidar techniques using differential absorption or resonance fluorescence may be employed. The limitations on seeing into the troposphere when viewing the limb dictate that these instruments be down-looking. In the near term, in-orbit observation will focus on column

abundances. Farther in to the future, there will be a need to determine vertical profiles of several species.

The species to be measured, if possible, include OH and O₃, which interact with the various different cycles; NH₃, NO₂, and HNO₃ from the nitrogen cycle; dimethyl sulfide, H₂S, and SO₂ from the sulfur cycle; and CH₄, nonmethane hydrocarbons, and volatilized metals such as CH₃Hg and Hg. If a means can be found for remotely observing CO₂ and N₂O to better than 1 percent accuracy, then the variations in these relatively abundant trace constituents would be important to monitor from space.

(2) Direct Tropospheric Wind Sensing

As discussed earlier, the direct measurement of lower atmosphere winds appears feasible using the Doppler shift in the return signal from a laser pulse transmitted

into the atmosphere. The Doppler lidar has some of the basic characteristics that were described in the previous section where the Lidar Atmospheric Sounder was discussed, however, due to the high spectral resolving power required to monitor the tropospheric winds, this instrument is conceived as being specialized for this task alone. Several implementations of the Doppler lidar are presently being studied. Given the acute need for high spatial resolution observations of the wind system in the troposphere, a flight-qualified instrument should be ready in the 1990s. The expected spatial resolution of these measurements will be on the order of 1 km in altitude and a few degrees in latitude and longitude. However, as with the High-Resolution Imaging Spectrometer (HIRIS), it will be desirable to select ground targets where higher resolution is required. The velocity accuracy of the Doppler lidar should be about 1 m/s throughout the troposphere. To some extent, a trade-off can be made between velocity accuracy and spatial resolution. These measurements could be used directly, or they can be applied through a global circulation model to enable global atmospheric transport to be obtained.

(3) Upper Atmospheric Composition

In addition to the reasons discussed earlier, limb viewing is the most effective method for sounding the upper atmosphere, because the long path and black background enhance the sensitivity to the small signal from trace gases and the observing geometry provides high vertical resolution. For these reasons, the instruments for observing the upper atmosphere are limb sounders.

These measurements have several objectives. One is to obtain measurements over a long period of time of the species which are necessary to assess any long-term changes in the atmosphere and determine the reasons for them. At present it is reasonable to predict that measurements of several gases will be required, but other than the certain need to continue measurements of ozone and temperature (as shown in Figures 18 and 19) the selection of other gases requires the insight which the results of UARS should provide. Among the gases that would be considered are sources of stratospheric radical species such as H_2O , N_2O , CH_3Cl , CH_4 , and chlorofluorocarbons, some radical species including OH, HO_2 , NO, NO_2 , and ClO, and some chemicals which function as either less active temporary reservoirs of trace elements or more long-lived species through which trace elements are lost from the upper atmosphere through exchange with the troposphere, such as HNO_3 , ClONO_2 , H_2O_2 , H_2CO , HCl, N_2O_5 and HNO_4 . A second objective is to augment the UARS observations by measuring additional species and extending the altitude and latitude range of the UARS measurements of some species.

Most of the gases listed above have spectral features between the UV and microwave parts of the spectrum. These permit detection and measurement of the gas concentration through analysis of radiation emitted, scat-

tered, or absorbed by the atmosphere.

(a) Infrared Radiometry and Spectroscopy

The infrared spectrum of the atmosphere contains an extremely large number of discernible features, which permit the quantitative derivation of mixing ratios of many of the gases of interest by infrared radiometers and/or spectrometers. In either case, measurements of the precision and sensitivity needed in the 1990s will require detectors and optics which are cooled either actively or by cryogenics to temperatures well below 100° K, and perhaps to only a few degrees K. A spectrometer capable of scanning a significant spectral range would have the advantage of providing a tool to observe a large number of species and to explore for additional ones.

An example of the type of instrument which could address this type of needed measurement would be a cryogenic, infrared interferometer spectrometer. Such a device would have a spectral scan capability of from 2.5 to 16 microns with a spectral resolution of 0.1 cm^{-1} or less. The altitude range of the observations could extend from 15 to 120 km with vertical resolution of about 3 km, or roughly half an atmospheric scale height. The data rate of such a device would be quite high, and this might necessitate the inclusion in the instrument of alternate observing modes capable of providing measurements of only a selected set of species on a continuous basis. Gases which could be easily measured using this instrument would include O_3 , H_2O , HNO_3 , NO_2 , CH_4 , N_2O , NO, CO, CFC1_3 , CF_2Cl_2 , and possibly ClO and ClONO_2 .

In addition, a number of key gases could be measured continuously, with higher spatial and temporal resolution, using a multi-channel IR radiometer. This technique has been demonstrated for O_3 , H_2O , N_2O , NO_2 , HNO_3 , CH_4 and temperature. Additional gases include NO, CF_2Cl_2 , and HCl. Vertical resolution could approach 2 km, with 500 x 500 km spacing.

(b) Submillimeter Observations

This spectral region is rich in spectral features, but many overlap the large number of H_2O and O_3 transitions. It could be used to profile the concentrations of OH, HCl, and HF, as well as H_2O and O_3 . The technology for these devices is not as advanced as that for infrared remote sensing. A cooled interferometer spectrometer, with detectors at $\sim 3 \text{ K}$ and a resolution of 10^{-3} cm^{-1} , could be used. Alternatively, a multichannel radiometer might also be used. The vertical resolution would be $\sim 3.5 \text{ km}$ with scans lasting several seconds.

(c) Microwave Limb Sounder

The microwave spectral region is currently being used to measure ClO in the atmosphere. An instrument such as the Microwave Limb Sounder on the UARS could be employed. For each spectral feature, the signals are converted to a common center frequency, and separated by a band of filters into signals in each of 15 channels of variable width. This technology can also measure kinetic temperatures, N_2O , H_2O_2 , and O_3 to 90 km. A common

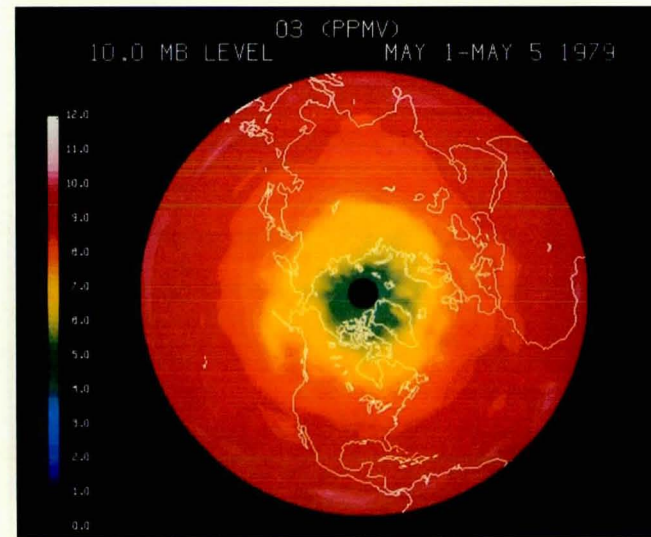
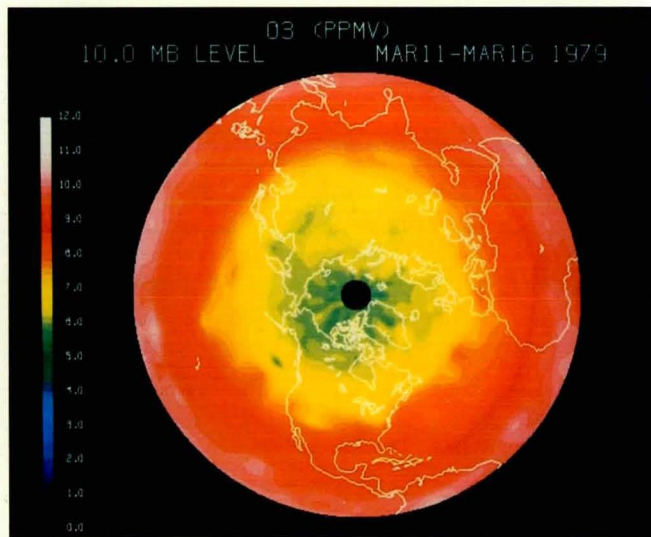
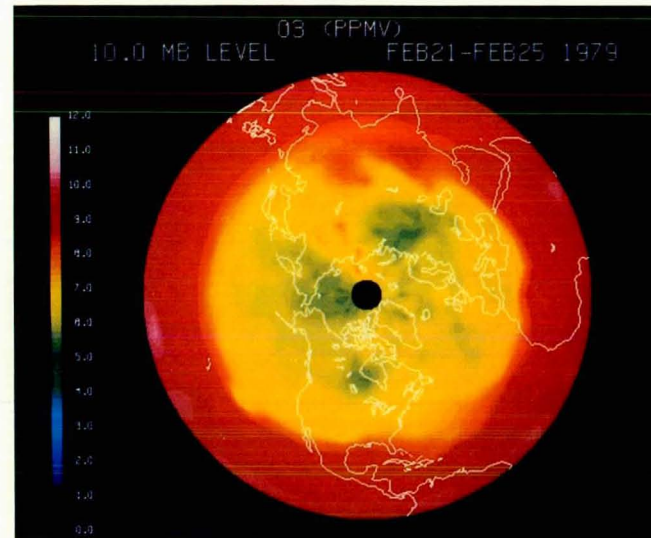
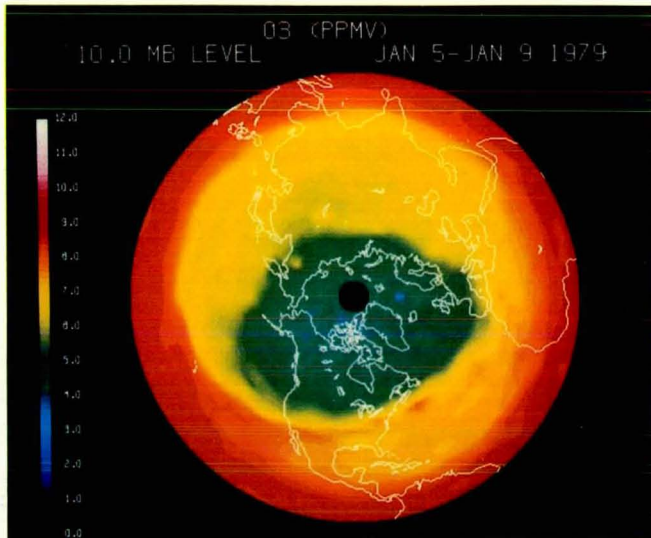


Figure 18. Global variation of ozone in the northern hemisphere at the 10 mb level as observed by LIMS.

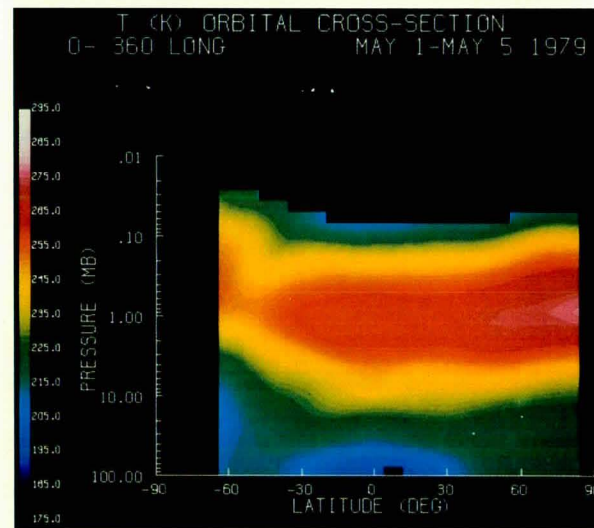
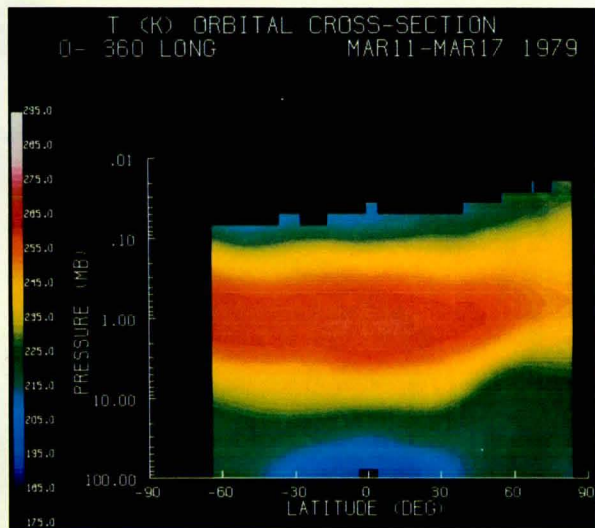
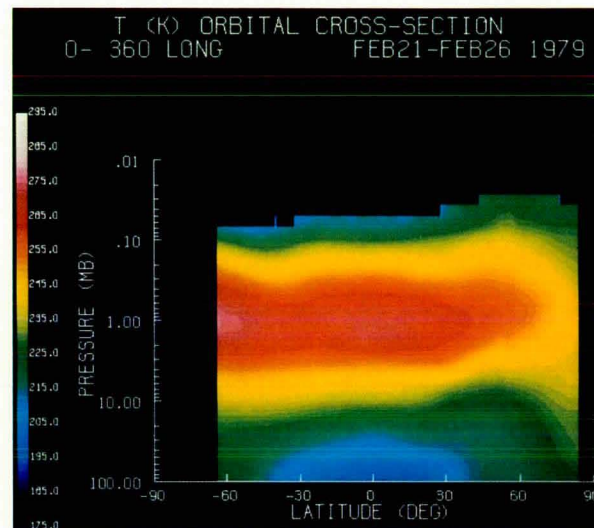
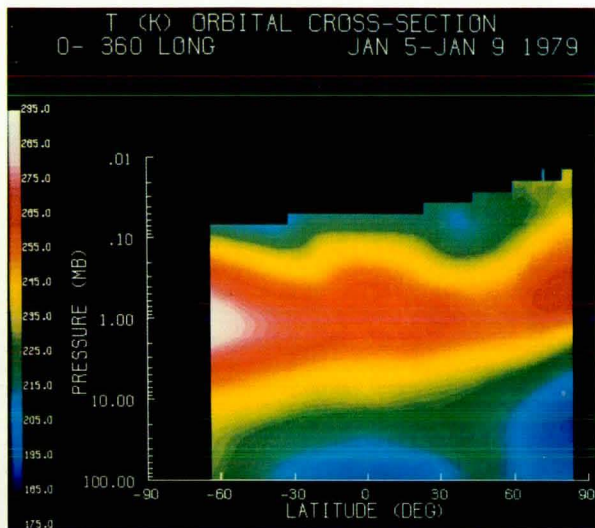


Figure 19. Variation of zonally averaged atmospheric temperature with respect to latitude and height as observed by LIMS.

antenna can be shared by a group of detectors in order to provide an instrument which measures a small group of species

(d) Visible and Ultraviolet Measurements

Some atmospheric constituents such as atoms and metastable species, which become particularly important in the mesosphere, are most easily measured using visible and/or ultraviolet spectral emissions. This instrument is a set of conventional spectrometers which use array detection to measure the spectrum of light emitted or scattered from the Earth's atmosphere. The spatial sampling can be controlled by the direction of the instrument slit, to act either as a "pushbroom" to view down through the atmosphere directly, or as a fixed, limb-scanning instrument to provide altitude profiles at high resolution along the spacecraft track. Spectral dispersion provides the second array direction, with the spectral resolution determined by the number of elements in this dimension on the detector. Working at modest resolution (e.g., 3 nm) this instrument would provide global maps of stratospheric ozone, total column content of H₂O, NO₂, O₂, and other minor gases, thermospheric densities of O, N, H, N₂, O₂, NO, and a series of metastable species which are abundant in the upper regions of the atmosphere.

(4) Upper Atmospheric Wind Sounding

A High-Resolution Doppler Observatory to determine upper atmosphere winds would be composed of at least two basic, very-high-resolution spectroscopic devices. The primary passive wind and temperature monitor is a high-resolution, multiple-etalon Fabry-Perot interferometer which is capable of measuring the Doppler shift of both molecular absorption lines as well as bright molecular and atomic lines which are emitted from the high atmosphere. This device is capable of measuring the vector wind with a component accuracy of a few meters/sec from the tropopause to near the stratopause, with a small break near 50 km, then measuring the wind from about 60 km to the exobase with accuracy beginning at the few meters/sec level and degrading to about 10 m/s at the exobase. High-resolution instruments of this kind have limitations on their spatial coverage, which will be on the order of a few degrees along the spacecraft track. The principal spectral features that will be measured result from absorption and scattering of light by molecular oxygen and water vapor at low altitudes. At higher altitudes, light emitted by molecular oxygen, atomic oxygen, and the atomic oxygen ion will be used to discern the wind and temperature. It should be noted that high-resolution spectroscopy in the visible and near-infrared ranges has the inherent capability of measuring the altitude distribution of aerosols, water vapor, carbon dioxide, temperature, pressure, and winds, using the information content within individual absorption lines in the spectrum of light reflected by or emitted from the atmosphere. Selectively chosen spectral lines have the optical depth variability that is used by lower-resolution,

infrared nadir-sounding instruments in routine use at the present time.

The second component of this instrument set is a wide-angle Michelson interferometer using array detection to resolve at high spatial resolution the wind and temperature at high altitudes. This type of instrument has very high throughput, and thus can resolve smaller spatial scales when the spectral feature being observed is very simple in form, such as a single isolated spectral line. The wind structure in the upper mesosphere and lower thermosphere, where strong wave breaking is occurring, would be observed, the detailed structure of the polar atmosphere could be resolved, and the structured night-time thermosphere would be routinely studied.

(5) Energy Input Monitors

There is a strong need in the study of Earth to maintain a long-term measure of the solar and magnetospheric energy sources which drive the major atmospheric circulation systems, as well as to have available the planetary surface exchanges which will be observed with SISP and SAM. A series of smaller instruments should be included on EOS if they are not part of an operational satellite payload which will maintain our observations of the solar spectral irradiance, the solar-constant, magnetospheric particle inputs, and magnetospheric electric fields and currents which are the primary sources of energy to our atmosphere.

Attitude and Orbital Requirements

The APACM will utilize many remote sensing techniques which either are limb viewing or direct Earth viewing, but which all require a high degree of orientation accuracy. The primary driver for the precision of the orientation knowledge and control are the wind measuring devices, which must discern a velocity shift of 1-2 m/s from a spacecraft moving at 7,500 m/s. These requirements lead to a need to know the spacecraft orientation to about 30 arc seconds on all axes. The IR limb sensors, which are viewing a sharply stratified horizon, can tolerate larger pointing errors but need stabilities of 5×10^{-3} degrees/sec.

The orbital requirements for this element of the EOS are somewhat more relaxed than the attitude requirements. However, there is a desire to simplify the sampling comb so that local time is not mixed with seasonal changes. This has led to the selection of a sun-synchronous orbit to eliminate this local time/season confusion. There is a desire to have the orbit fixed so that the equatorial crossing occurs in either mid morning or mid-afternoon. Ultimately, it would be desirable to have spacecraft at both time periods which contain identical instrumentation. It is also important to keep the orbit of the earth-viewing mappers and the atmospheric APACM in the same plane, for sampling overlap and to satisfy the desire for Space Shuttle servicing to be efficiently carried out on a single mission.

The orbit being suggested for these observations is identical to that recommended for the SISP package—sun-synchronous with a 2 00 p m equator crossing time. This choice results from a judgment as to which science goals will be paramount in the 1990s within a multidisciplinary context. The diurnal variation in the atmosphere is quite pronounced. As explained earlier, orbits which provide global observations are either sun-synchronous or have slow rates of precession through local time which convolve diurnal with seasonal or annual effects. For the upper atmosphere, where limb-scanning techniques are possible, this may be avoided to some extent because limb observations of the poles can be obtained from orbits as low in inclination as 70 degrees. In this case, the rate of orbit precession through a full diurnal cycle is about 56 days and provides two observations at a given time of day during each season. Given the study of diurnal effects in the upper atmosphere by UARS, the need for obtaining this degree of diurnal variation in local observing times is not compelling. The recommendation of a 2 00 p m local time is not highly constrained, but has been chosen to provide a time at which the daytime chemistry of the atmosphere is fully developed and many diurnally-varying species are at the extreme range in their daily cycle in concentration. By 2 00 a m local time, the decay of daytime species is quite advanced and the extremes in day-night variation can be observed. The preceding arguments are based primarily on the chemical composition measurement needs. Should the tropospheric wind measurements be implemented separately, the choice of crossing times would be driven more by the diurnal cycle in cloudiness to maximize the number of observations and the availability of simultaneous meteorological measurements of temperature, clouds, moisture, and precipitation to improve the scientific utility of the data. The choice of 2 00 p m would satisfy this second consideration, given the presence in this orbit of other EOS components as well as one of the operational NOAA satellites.

IN SITU MEASUREMENTS OF POTENTIAL FIELDS AND PLASMAS

The three sensor packages described in this section do not address *in situ* geophysical measurements but concentrate on remote sensing techniques. We do not mean to slight the needs for *in situ* experiments during the next decade. It should be pointed out that the orbit and spacecraft characteristics for these measurements will probably be quite different from those envisaged for the EOS missions.

The requirement for potential field measurements beyond those envisaged for GRM rests on (1) ability to make measurements with more accuracy and horizontal resolution than GRM, and (2) the need for continued measurements of the same quality as GRM. The second aspect is less problematical because of the need to mon-

itor secular changes in the global magnetic and gravity field on the scale of about once per decade. The first aspect, the ability to improve on GRM, rests on the ability to improve technology in such areas as, for example, orbit maintenance in the presence of atmospheric drag, tethered systems, and gravity gradiometers.

SCIENCE AND INFORMATION COORDINATION AND MANAGEMENT FOR EOS

The interdisciplinary themes, the expected longevity of EOS, and the associated data management complexities offer special problems with regard to coordination, management, and continuity of the science objectives and the information system. As discussed, much thought and consideration should be given towards fostering interdisciplinary science and to the development of the information system. A distributed information system seems logical. The need for leadership in terms of standards, protocols, software development, and data compatibility call for more than a distributed system with nodes of equal weight. Also, the needs for long-term archiving and data continuity call for a structure beyond a distributed system. We recommend that the coordination and management functions be assigned to an organization that has a longevity that supersedes any individual data node. In addition, that organization could act as a focus for coordination of mission operation activities, and it could act as a location for the community to utilize as a focal point of scientific collaboration. The organization, acting in effect as a major or lead node in a distributed system, could also house a backup data archive to assure data continuity. We point out that the organization would be a new concept for which there are no existing role models.

SUMMARY

In this chapter, we have described a candidate implementation of an integrated system which is necessary for the solution of most of the scientific problems described in Chapter I. Our approach relies upon a phased, four-step implementation strategy, including both a scientific management function and requisite hardware deployment. It should be emphasized that this is indeed an information system and not just a data collection facility. While the collection of data is a necessary part of the system, the other parts are equally and perhaps more important, providing an integrated capability which inherently includes a major new thrust in interdisciplinary Earth sciences research.

In addition to a complete information and data base management system, three complementary sensor packages and an ADCLS have been proposed as new space-based assets. These new capabilities are summarized in Table 4. Some of the instruments represent groups of

TABLE 4 EOS Instruments

Instrument	Measurement	Spatial Resolution	Coverage
1 Automated Data Collection & Location System (ADCLS)	Data and command relay and location of remotely sited measurement devices	Location to 1 km for buoys, to 1 m for ice sheet packages	global, twice daily
SISP—Surface Imaging & Sounding Package			
2 Moderate Resolution Imaging Spectrometer (MODIS)	Surface and Cloud imaging in the visible and infrared 4 nm-2 2 nm, 3-5 μm, 8-14 μm resolution varying from 10 nm to 5 μm	1 km × 1 km pixels (4 km × 4 km open ocean)	global, every 2 days during daytime plus IR nighttime
3 High Resolution Imaging Spectrometer (HIRIS)	Surface Imaging 4-2 2 nm 10-20 nm spectral resolution	30 m × 30 m pixels	pointable to specific targets, 50 km swath width
4 High Resolution Multifrequency Microwave Radiometer (HMMR)	1-94 GHz passive microwave images in several bands	1 km at 36 5 GHz	global, every 2 days
5 Lidar Atmospheric Sounder and Altimeter (LASA)	Visible and near infrared laser backscattering to measure atmospheric water vapor, surface topography, atmospheric scattering properties	vertical resolution of 1 km, surface topography to 3 m vertical resolution every 3 km over land	global, daily atmospheric sounding, continental topography total in 5 years
SAM—Sensing with Active Microwaves			
6 Synthetic Aperture Radar (SAR)	L, C, and X-Band Radar images of land, ocean, and ice surfaces at multiple incidence angles	30 m × 30 m pixels	200 km swath width daily coverage in regions of shifting sea ice
7 Radar Altimeter	Surface topography of oceans and ice, significant wave height	10 cm in elevation over oceans	global with precisely repeating ground tracks every 10 days
8 Scatterometer	Sea surface wind stress to 1 m/s, 10° in direction Ku band radar	one sample at least every 50 km	global, every 2 days
APACM—Atmospheric Physical & Chemical Monitor			
9 Doppler Lidar	Tropospheric winds to 1 m/s doppler shift in laser backscatter	1 km vertical, 2° longitude, 2° latitude	global, twice daily surface to 100 mb
10 Upper Atmosphere Wind Interferometers	Upper atmospheric winds to 5 m/s, doppler shift in O ₂ thermal emissions	3 km vertical, 2° longitude, 2° latitude	global, daily
11 Tropospheric Composition Monitors	Trace chemical constituents of the troposphere	varies from total column density to 1 km vertical, from 1° to 1° horizontal	global, daily, surface to 100 mb
12 Upper Atmosphere Composition Monitors	Trace chemical composition passive emission detectors at wavelengths from UV to microwave	3 km vertical 2° longitude, 2° latitude	tropopause to 120 km global daily day and night coverage
13 Energy and Particle Monitors	Solar Emissions from 150-400 nm, 1 nm spectral resolution Earth radiation budget Total Solar irradiance Particles & fields environment	total solar output	roughly continuous sampling, at least twice daily for solar observations

related sensors which would be combined to achieve a given capability. Some of the sensors embody mature technology already existing and demonstrated by previous satellite deployments, but there is a clear need for the development of new, smart sensors. This work must begin immediately if we are to implement the Earth Observing System in the next decade. More fundamentally, what we seek is achievable only in concert with

a long-term commitment to implement now queued Earth science research missions, planned operational remote-sensing systems, and a well-founded research and development program including both science and engineering.

Taken as a unit, the four-phase, integrated Earth Observing System defined here will provide a tool for stimulating revolutions in our understanding of Earth science.

IV. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Earth science is already faced with problems that are truly global in extent and interdisciplinary and multidisciplinary in nature. The problems of the 1990s are expected to be even more strongly interdisciplinary. Since the land, ocean, and atmosphere are coupled, many of the foremost questions can no longer be treated in isolation, but require observations of the system as a whole. Progress can be made piecemeal, but the interdisciplinary questions require observations and effort across the broad spectrum of Earth science. An important example is the study of biogeochemical cycles, the processes by which key chemical elements are transformed and exchanged among the soils, biota, inland waters, oceans, and atmosphere. A second example is the hydrologic cycle, in which water is cycled among the oceans, atmosphere, cryosphere, and land surface while undergoing phase changes and redistributing energy within the Earth system. While these are distinct problems, they are also important parts of the study of climate in which the interactions among atmospheric composition, soil moisture, surface albedo, cloud amount, ocean heat transports, and atmospheric dynamics couple together to determine the environment in which life takes place. These global problems are vital to all the inhabitants of our planet, progress toward solving them will require the creative involvement of the international scientific community.

Many of the phenomena studied by Earth science can be observed and understood only through consistent measurements over time periods of many years. This includes observations at spatial scales ranging from the global scales attainable from space to localized *in situ* measurements. At present, operational meteorological and land satellite observing systems are providing the beginnings of scientifically essential, long time-series data sets. This operational activity should be continued, with the data being taken and saved so as to ensure its utility in research. The increased use of these data in addressing the science issues we have identified should begin now. New programs of scientific observation should be initiated and sustained to broaden the scope of the observations being made.

Developments in observational requirements and in remote sensing instrument technology suggest that future satellite observing systems should be conceived and implemented to address multidisciplinary needs in Earth science. In the past, the instruments for observing Earth have been designed to serve the specific needs on individual Earth science disciplines. Current experience with instruments such as the AVHRR has shown that data from these meteorological sensors are quite useful for the study of land surface processes. Studies of the

use of space-based, synthetic aperture radar indicate that this technique can be of use in studies of the cryosphere, geology, and vegetative land cover and that it may be useful in physical oceanography. These examples are harbingers of a future in which technologies which are now emerging may enable the development of instruments which are designed to serve multidisciplinary needs. Such developments clearly support the emerging interdisciplinary focus of Earth science. Also, this study has pointed out that there are many cases where observations of a particular phenomenon are required by several disciplines.

Earth science is a data-intensive activity, and in its broadest sense, the data system will be the key to timely progress in the understanding of our planet. The combination of developing measurement possibilities can provide an unprecedented amount of information on the solid earth-land, surface-ocean-atmosphere-biosphere-cryosphere system. Spectral imagery can provide detailed information on, for example, surface rock and soil types, land use, surface vegetation and its changes, ice sheet extent, and phytoplankton concentrations. Altimetry is capable of yielding sea, land, and ice surface topography, as well as eddy motions in the ocean. Passive sounding methods are giving atmospheric temperature, winds, composition, sea surface temperature and water vapor, while active sounding has the potential for improved vertical resolution, sensitivity to minor species, and tropospheric wind determination. Other measurements yield surface winds over the ocean, information on soil moisture and vegetation, and perhaps precipitation.

As a consequence, large amounts of data will be obtained. Special consideration needs to be given to the collection, processing, dissemination, and archiving of these data, and to foster their use in the investigation of interdisciplinary science problems.

RECOMMENDATIONS

- (1) A program must be initiated to ensure that present time series of Earth science data are maintained and continued. Collection of new data sets should be initiated.**

The study of Earth science processes often requires long time series to resolve the inherent long time-scale fluctuations present in these processes. While our emphasis is on time series of data collected from low Earth orbit, we recognize the importance of associated, nonsatellite *in situ* data sets and data collected from spacecraft in geosynchronous orbit.

Within this recommendation, we recognize the following specific requirements:

- (a) The currently planned NASA Earth science research missions UARS, TOPEX, GRM, and ISTP should be initiated. The shorter duration science missions and instrument development flights on the Space Shuttle also need to proceed.
- (b) Operational satellite systems that provide data of interest to Earth science should be continued. Currently proposed additions to this capability should be implemented.

This includes satellite systems of agencies of the U S Government as well as those of foreign governments. Efforts should be made to maintain these observational capabilities on a permanent basis or until their observational abilities have been replaced by new systems.

- (c) The Advanced Data Collection System, together with instruments having the capabilities exemplified by the SISP, SAM, and APACM instrument packages described in Chapter III, should be placed in orbit together long enough to produce useful data series on trends and interannual variability (at least for the order of a decade).

While it is not essential that these packages be launched at the same time, it is imperative that eventually all of these observational capabilities be in orbit simultaneously and operated together long enough to produce useful data series on trends and interannual variability (at least for the order of a decade).

- (d) A continuing program of instrument development should be augmented, supported, and maintained.

Some of the instruments of the Earth Observing System can be ready in the 1990s only if their development is initiated in the near future. The time lag between the definition of an instrument concept and the initiation of successful, continuous operation from space is such that it is essential that a coordinated, ongoing program of instrument development be in place. Rapidly evolving technologies are constantly adding to our ability to observe Earth processes, and where possible these should be used to upgrade the EOS capability.

(2) A data system that provides easy, integrated, and complete access to past, present, and future data must be developed as soon as possible.

Satellite data have presented considerable problems to Earth scientists in the past. It has been difficult to locate, access, and process a particular piece of data of interest to a science problem, and such difficulties

have severely restricted the use of satellite data. Satellite data cannot be effectively used to understand global processes unless such a data system exists, and to the extent that these data are essential for progress in this area, improvements in understanding will not occur.

Within this recommendation, we recognize the following specific requirements:

- (a) Establishment of the data management system should begin as soon as possible. It is essential that the data system be in place well before the launch of any major new observational capabilities such as SISP, SAM, and APACM. Such a system will allow the expansion of work with existing data sets. This is one of the most important elements of EOS.
- (b) Data sets from current operational and research satellites should be continued, enhanced, and made accessible. This includes the presentation of data in standardized forms and terms of reference whenever possible. These data sets cannot be allowed to disappear as a result of neglect. In addition, such data sets must make use of new data storage and access technologies as they are made available. Continuity and comparability of data within these time series must be ensured.
- (c) The data management system must provide easy, integrated access to existing data and provide a framework for supporting new data sets. Scientists must be able to interrogate the data system in several ways in order to locate data of interest, determine the quality of data, and obtain the data. Such a system must be able to handle multiple sensors, correlative *in situ* data sets, and distributed archives.
- (d) It is essential that the data sets have the necessary algorithms available for processing raw data to corrected, geophysical units (e.g., leaf area, ocean chlorophyll, etc.). Although it is recognized that final algorithms for new instruments cannot be in place before launch, preliminary algorithms must be in place before launch. A continuing program of algorithm verification and development must be maintained after launch.
- (e) Proper communication links and data base management are necessary for coping with a distributed data system. In particular, high data rates will be necessary for transmission of images and other large data sets. It is also essential that the data base maintain tracking on processing performed on particular data sets at these distributed archives.
- (f) NASA should undertake negotiations with effective national and international organizations

where these organizations will provide useful data for Earth science. Any attempt to understand global processes will require international involvement in data collection and scientific understanding.

(3) A long-term research effort must be sustained to study and understand these time series of Earth observations.

As the investigation of many Earth science processes requires a long time series of observations, it also requires a long-term commitment to research. The potentially vast amounts of data will necessitate a sustained research activity in order to achieve the understanding of these complex processes. Observational capabilities and a data system are only tools which are needed by the research effort in order to produce improved information and understanding.

Within this recommendation, we recognize the following specific requirements:

- (a) Sufficient scientific personnel must be available to assimilate and understand these data sets. This includes both use of established Earth scientists familiar with remote sensing and training programs for graduate students and others unfamiliar with remote sensing. New intellectual talent must be attracted to all areas of this activity.
- (b) Sufficient funding to maintain long-term research programs and data sets implies not only a level of support but freedom from major fluctuations in funding levels for essential efforts which maintain high standards of quality.
- (c) The individual disciplines of Earth science should be kept strong so that they can collaborate effectively.

(4) The Earth Observing System should be established as an information system to carry out those aspects of the above recommendations which go beyond existing and currently planned activities.

EOS can serve as a focal point for the observation and study of Earth using observations from space in the 1990s. A focal point is necessary for this system to capitalize on the advantages of a coordinated multidisciplinary approach using large data sets from a variety of sensors. This focal point should function as the lead node or site within a distributed scientific and information network.

Within this recommendation, we recognize the following specific requirements:

- (a) This facility should be responsible for the collection of data from the new sensors. This will include management of the ground-controllable sensors as well as planning for future

sensor modifications to currently operational EOS sensors.

- (b) EOS should be responsible for management of time series from the new sensors. The use of the time series requires that easy and quick access be available to Earth scientists and that the data be maintained in a consistent and comparable manner.
- (c) This facility should help provide easy access to independently obtained and maintained data sets relevant to Earth science research. It is essential that non-EOS data sets be available in a manner similar to EOS data sets. EOS should also provide the research community with a focus for advocating the maintenance and enhancement of these outside data sets.
- (d) EOS should provide the environment for the interpretation of these data sets. Special tools and methods will be necessary for the manipulation and processing of these large, complex data sets. It is necessary to provide an environment which encourages and facilitates collaboration between Earth scientists from different disciplines working on complex, multidisciplinary problems.

(5) The scientific direction of the Earth Observing System should be established and continued through an international scientific steering committee.

EOS will require close scientific management to ensure its maximum utility in meeting the research needs of the diverse Earth science community. EOS must maintain high scientific standards.

Within this recommendation, we recognize the following specific requirements:

- (a) The membership of the scientific governing committee must be drawn from all Earth science disciplines. As the various disciplines have different research needs, it is essential that these needs be recognized. This will aid in the solution of problems of concern to individual disciplines, as well as foster the solution of the broader interdisciplinary problems.
- (b) The scientific governing committee must ensure cooperation between EOS and other Earth science activities. The scientific governing committee should maintain close scientific contact with scientists throughout the world involved in other flight projects and in gathering *in situ* data sets.
- (c) The scientific governing committee must ensure that scientific user needs are being fulfilled on a timely basis by EOS.

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16. Abstract The Earth Observing System (EOS) is a planned NASA program, which will carry our multidisciplinary Earth science studies employing a variety of remote sensing techniques in the 1990's, as a prime mission, using the Space Station polar platform. It's primary goal is the generation of long term Earth science data sets of measurements and processes in the areas of agriculture, forestry, geology, hydrology, oceanography, snow and ice, troposphere and upper atmospheric chemistry, radiation and dynamics pertaining to global studies of Earth as a system, emphasizing the interactions and couplings of the atmosphere-ocean-land-cryosphere system. These results will provide the information needed to qualify our understanding of the global hydrological cycle, global biogeochemical cycles and global climate processes. This report provides the science rationale, recommended observational needs, the broad system configuration and a recommended implementation strategy to achieve the stated mission goals. The report is one volume of a proposed five volume set constituting the Phase A report as the Earth Observing System (EOS).			
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