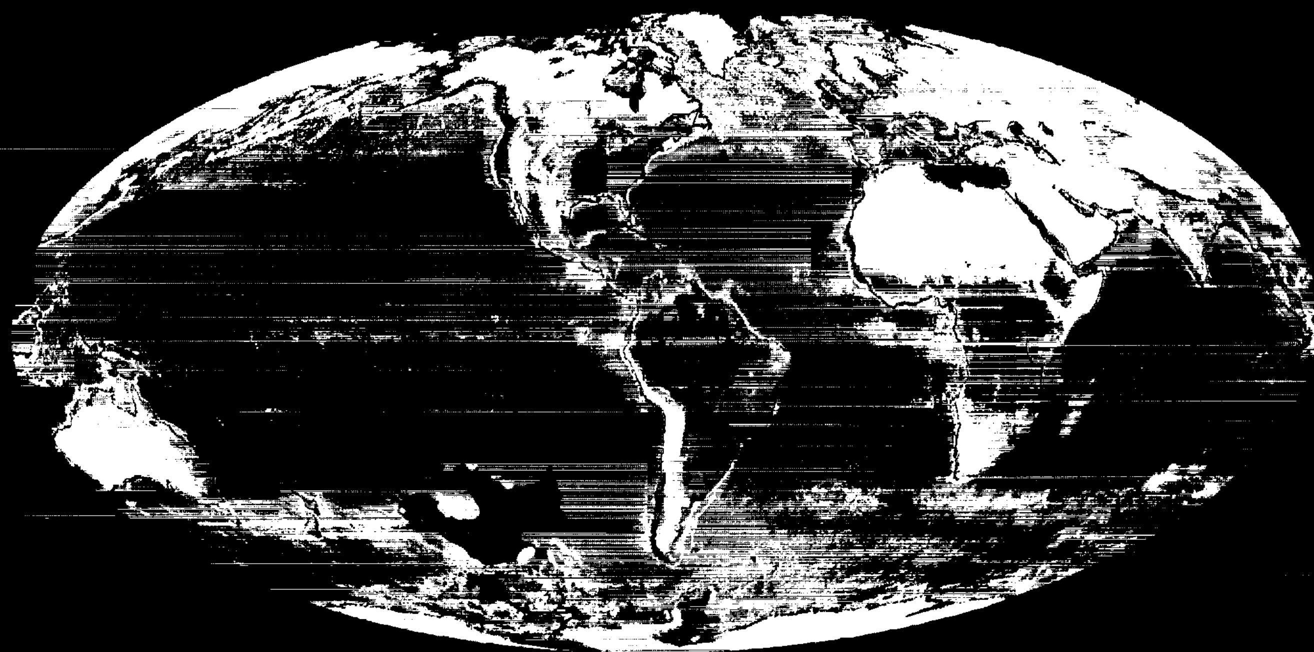

The Highlights of 1989

(NASA-TM-104985) THE HIGHLIGHTS OF 1989 (NASA) 77 p CSCL 13B N91-24669
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NASA

Earth Science and Applications Division

The image on the front cover shows the first truly global view of the Earth's biosphere. The composite image of the ocean chlorophyll concentration was produced from 31,352, 4-km resolution CZCS scenes from November 1978, through June 1981, each of which corresponds to approximately 2 million square kilometers of ocean surface. Nearly 400 billion bytes of raw CZCS data located on more than 12,000, 9-track computer tapes were used to make this image. Land vegetation patterns are derived from three years of daily images from NOAA-7's visible and near infrared sensors (credit: C. J. Tucker, NASA/GSFC). More details of this work are given in Chapter Six.

NASA
EARTH SCIENCE AND APPLICATIONS DIVISION

HIGHLIGHTS OF THE YEAR
1989

National Aeronautics and Space Administration
Washington, D.C. 20546

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Foreword

This is the third year on which the Earth Science and Applications Division (ESAD) has reported to the research and applications community on its current activities and future plans, although the 1989 format is a little different from those of previous years. As indicated by the title, this third report *Highlights of 1989* focuses on topics of particular interest at this time of transition in the Earth sciences, rather than providing a comprehensive description of all programs within ESAD. Chapter 1 does offer an overview of the work of the Division, and the main changes in previously announced flight schedules are noted.

We have constantly stressed the importance to the research and applications community of timely and relevant information about the latest expeditions, the newest findings, and the upcoming directions upon which ESAD has embarked and will pursue in the future. This report is part of our ongoing endeavor to achieve and maintain good communications with the Earth science research community, across government and in the academic arena, nationally and internationally.

Amongst the many achievements of the Division in 1989, one heavy loss was suffered when Dr. Edward G. Flinn passed away after a long illness, valiantly combatted. It is seldom that a single individual has had as great an impact on his scientific community; the spectacularly successful international cooperation in NASA's Crustal Dynamics Project is exemplary of Ted Flinn's broad vision and scope. He will be sorely missed.

S. G. Tilford
Director
Earth Science and Applications Division
NASA Headquarters, Code EE

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1

Overview

Very significant progress has been made this year in setting Earth science research in global change on track for the twenty-first century. In the 12 months since the last Earth Science and Applications Division (ESAD) Annual Report was published, several major milestones have been reached:

- The selection of instruments and science investigations for the NASA Earth Observing System (EOS) platforms and the start of definition-phase contracts
- The implementation of the Arctic stratospheric ozone expedition and the publication of preliminary results
- The implementation of the FIFE-89 experiment to understand the biophysical processes governing interactions between the land surface and the atmosphere
- The publication of the Committee on Earth Science (CES) report *Our Changing Planet: The FY 1990 Research Plan*, to which ESAD made a substantial contribution
- The endorsement by President Bush of Mission to Plant Earth as a "critical part of our space program" on the 20th anniversary of the Apollo 11 mission.

This presidential endorsement demonstrates recognition of growing concern over the increasing demands of human habitation and economic development on the planet Earth. This concern has focused political and scientific attention on a range of natural and human processes that threaten the global environment—including ozone depletion, possible global warming, regional acid rain damage, deforestation, ocean pollution, and desertification.

It is now well established among the international Earth science community that adequate understanding of the long-term impact of such problems can only be achieved through both single- and multidisciplinary, fully integrated studies of the Earth, based on recognition of this planet as a single, interacting system. Scientists must first understand the underlying physical, chemical, and biological processes that control the Earth's interrelated ecosystems in order to fully comprehend the impact of interlocking natural and human processes on the present and future global environment.

Committee on Earth Sciences

In response to scientific concern about these global issues, and the requirement for an interdisciplinary approach, the Committee on Earth Sciences (CES) was established by the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET), under the directive of the President's Science Advisor. CES consists of 13 federal agencies with programmatic responsibilities related to global change. Among the CES members, seven are federal agencies currently engaged in global change research, i.e., NASA, the National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), Department of Energy (DOE), U.S. Geological Survey (USGS), Environmental Protection Agency (EPA), and U.S. Department of Agriculture (USDA).

In January 1989, the CES report *Our Changing Planet: A U.S. Strategy for Global Change Research* was submitted to Congress with the President's Fiscal Year 1990 Budget. This report and the subsequent CES report *Our Changing Planet: the FY 1990 Research Plan* describe the purpose, functions, goals, and implementation strategies of CES. In defining its role, the CES has drawn on a number of major analyses of global change research requirements published in the last few years. These include the 1988 National Academy of Science (NAS) report, *Scientific Plan for the World Climate Research Program*; the 1988 report of the Earth System Science Committee, *Earth System Science: A Closer View*; and the 1988 International Council of Scientific Unions (ICSU) report, *The International Geosphere –Biosphere Program: A Study of Global Change—A Plan for Action.* The work of the CES will complement activities already under way in global change research such as the NAS Committee on Global Change; the National Climate Program; the International Geosphere-Biosphere Program (IGBP); the United Nations Environmental Program (UNEP) and the Intergovernmental Panel on Climate Change (IPCC).

The purpose of CES is "to increase the overall effectiveness and productivity of Federal R&D (research and development) efforts directed toward an understanding of the Earth as a global system . . . [and address] . . . significant national policy matters which cut across agency boundaries." CES functions include:

- Reviewing federal research and development programs in national and international Earth sciences programs
- Improving planning, coordination, and communication among federal agencies engaged in Earth sciences R&D
- Identifying and defining Earth sciences R&D needs
- Developing and updating long-range plans for the overall federal R&D effort in Earth sciences
- Addressing specific programmatic and operational issues affecting two or more federal agencies
- Providing reviews, analyses, and recommendations to the Chairperson of FCCSET on federal policies and programs related to Earth sciences R&D, especially in assessing the impact of human activites on the global environment

The U.S. approach to issues of global change requires research to understand the Earth's environment; R&D of new technologies to adapt to or mitigate environmental changes; and the formulation of national and international policy options for dealing with a changing environment. The goal of the U.S. Global Change Research Program is to provide the scientific basis for informed national and international decision-making on natural and human-induced changes in the global environment and on their regional effects. Accomplishing this goal will require scientific studies of past and present global changes; of the physical, geological, chemical, social, and biological processes involved in regulating global change and its environmental effects; and of the predictability of global change and its consequences.

The U.S. Global Change Research Program's implementation strategy involves 1) identifying three major scientific objectives; 2) integrating various scientific disciplines; and 3) integrating the program with other national and international global change activities. The three scientific objectives are:

- The establishment of an integrated, comprehensive monitoring program for Earth system measurements on a global scale
- A program of focused studies to improve understanding of the physical, chemical, and biological processes that influence Earth system global and regional trends and changes
- The development of integrated conceptual and predictive Earth system models

In order to achieve a greater level of integration among both single-disciplinary and multidisciplinary scientific activities, the U.S. program is focusing on seven interdisciplinary science elements: biogeochemical dynamics; ecological systems and dynamics; climate and hydrologic systems; human interactions; Earth system history; solid Earth processes; and solar influences.

Earth Science and Applications Division (ESAD)

NASA and its Earth Science and Applications Division (ESAD) clearly have a major role in the U.S. Global Change Program. ESAD is responsible for broad-based scientific studies from space of the Earth as an integrated whole. Associated efforts include suborbital and ground-based studies; remote-sensing and advanced instrument development; improving techniques for transmitting, processing, archiving, retrieval, and use of data; related scientific models; and other atmospheric, oceanographic, and land surface research activities. ESAD has historically provided basic research and space flight support for investigations of the major Earth system components through remote sensing. These studies encompass upper atmosphere/tropospheric chemistry, atmospheric dynamics and radiation (which includes climate), geodynamics, and land

and ocean processes. To meet the new requirements of global change research over the past few years, ESAD has developed an Interdisciplinary Research Program, which explores topics that cut across traditional Earth science disciplines. Under this program, ESAD has supported research to detect the global greenhouse effect; quantify the role of clouds in modulating the Earth's radiation balance; identify sources and sinks of trace gases in the atmosphere that can cause global warming; and increase understanding of the global hydrological cycle, which is so important for climatic balance.

ESAD support of Earth science programs includes:

- Aiding in the development of Earth science research needs
- Definition of mission and instrument concepts
- Mission planning and development
- Flight support for major satellite and Shuttle-launched instrument programs
- Validation of satellite data through ground-based measurement campaigns
- Utilization of satellite mission data in ongoing research and analysis

ESAD first published a report of its overall activities in May 1987, *Earth Science and Applications Division: The Programs and Plans for FY 1987-1988-1989*. This report provided a comprehensive description of programs in all branches of the Division. The second report, *Earth Science and Applications Division: The Programs and Plans for FY 1988-1989-1990*, updated the first report, within the context of the same kind of comprehensive program description. This third report, *Earth Science and Applications Division: Highlights of 1989*, focuses on the most noteworthy activities of the year, described in detail in each of the chapters following this overview, rather than providing a full description of all branch activities. Figure 1-1 lists current flight operations and future plans for ESAD and Table 1-1 lists current program contacts within the Division, reflecting some organizational changes and growth as the work becomes increasingly multidisciplinary, as we institute global change research organizationally, and as we move towards the EOS era. The Geodynamics Branch is now known as Solid Earth Sciences (see Chapter 9). Table 1-2 lists the main flight schedule changes since last year's report.

Mission to Planet Earth

Mission to Planet Earth, a new NASA concept to be implemented in conjunction with our international space partners, is the mainstay of NASA's contribution to the goals of the U.S. Global Change Research Program. On the occasion of the Apollo 11 anniversary ceremony on July 20, 1989, President Bush, recalling the vision of the Apollo astronauts of a "tiny, fragile, blue orb rising above the arid desert of Tranquility Base," heralded a major new national and international initiative to seek new solutions to environmental problems such as ozone depletion, global warming and acid rain. "And this initiative," he said, "Mission to Planet Earth, is a critical part of our space program."

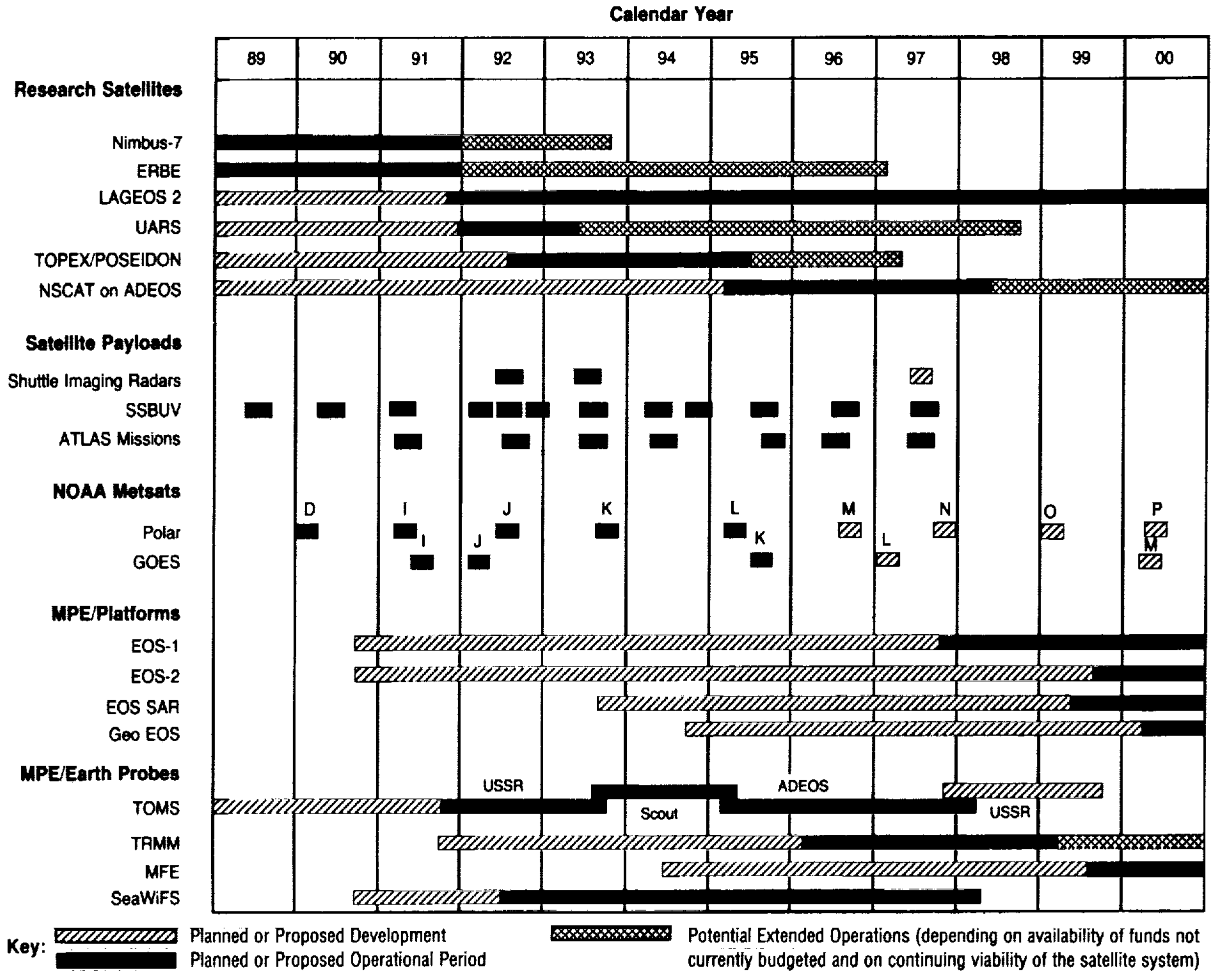
Mission to Planet Earth will enable scientists to undertake a wide range of investigations based on the interrelated observations of major Earth system components by a large variety of space-borne remote-sensing instruments as well as the findings of ground-based instruments, to begin to address the major environmental issues affecting the planet. Mission to Planet Earth also marks an important change in Earth science from single-discipline investigations to those that embrace a multidisciplinary approach in order to monitor the highly complex interactions among the many natural and human processes that promote balance or change in the global environment.

Participants of this international program include the European Space Agency (ESA), Japan's Science and Technology Agency (STA), Canada, and a wide range of federal agencies besides NASA and NOAA, which are playing leading roles. Space officials from over 23 nations have begun to coordinate the operation of over 20 Earth viewing satellites to be launched over the next 6 years.

As now envisaged, Mission to Planet Earth will entail the following space missions beginning in the 1990s:

- Unmanned Earth Observing System (EOS)–polar platforms carrying a wide array of research and operational remote-sensing instruments. Current plans call for the launching of five platforms; two supplied by NASA (NPOP-1; NPOP-2), one by STA (JPOP), and two by ESA (EPOP-1A and EPOP1B).
- Earth Probes–explorer missions of small satellites flying in low orbits over the Equator to complement the observations of EOS instruments: first flights will begin in the early 1990s.

FIGURE 1-1. **SATELLITE DEVELOPMENT AND OPERATIONS PLANS: LOW EARTH ORBIT AND SHUTTLE INSTRUMENTS.**



- The Space Station Freedom (SSF)—a permanently manned research laboratory with crews from participating countries: launch planned for 1995.
- Four or five large Advanced Geostationary Platforms; two supplied by the United States, and the others by the major space partners ESA and STA: first flight scheduled for 1999.
- A series of NOAA free flyers carrying operational instruments.

The Earth Observing System (EOS)

The Earth Observing System (EOS) is at the heart of Mission to Planet Earth. Defined as a "focused" effort by the CES, EOS is a multidisciplinary national and international observation effort to study interrelated changes in the Earth system and the roles of natural and human forces in this process. This program will continue for 25 years and is scheduled for a new start in 1991.

EOS will be jointly operated by NASA and NOAA in cooperation with the international space partners—ESA, Japan, and Canada. For 15 years, beginning in 1997, a comprehensive suite of highly sophisticated remote-sensing research and operational instruments on the polar platforms, the Space Station, and NOAA free flyers (already in flight) will provide continuous measurements of important elements related to the Earth's hydrological cycle, biochemical cycle, climate, and geophysical processes (i.e., atmospheric, oceanic, and solid Earth). Simultaneous measurements from the different EOS instruments will enable Earth scientists to conduct interdisciplinary investigations; for example, the impact of atmospheric forcing on oceans, or the interplay of climate, weathering, mountain building, and rapid plate boundary interaction in an alpine region.

TABLE 1-1. **ESAD PROGRAM CONTACTS**

Director	S. Tilford	453-1706
Secretary	M. Addison	453-1706
Special Assistant to Director	W. Huntress	453-1707
Program Support Specialist	G. LeSane	453-1706
Data Systems Activities	E. Njoku	453-1748
Solid Earth Sciences	M. Baltuck	453-1675
Applications Sciences	H. Frye	453-1675
Staff Scientist	N. Douglas	453-1675
Ocean Processes	S. Wilson	453-1725
Air/Sea Interaction	G. Lagerloef	453-1725
Polar Oceans	R. Thomas	453-1725
Ocean Circulation	G. Lagerloef	453-1725
Ocean Productivity	M. Lewis	453-1725
Land Processes	R. Murphy	453-1720
Terrestrial Ecosystems	D. Wickland	453-1720
Geology	M. Baltuck	453-1720
Hydrology	G. Asrar	453-1720
Technical Support		453-1720
Atmospheric Dynamics and Radiation	J. Theon	453-1680
Climate	R. Schiffer	453-1680
Global Scale	R. Kakar	453-1680
Mesoscale	J. Dodge	453-1680
Atmospheric Chemistry	R. Watson	453-1681
Upper Atmosphere Research Program/Global Change	R. Watson	453-1681
Atmospheric Theory	M. Prather	453-1681
Tropospheric Chemistry	R. McNeal	453-1681
Laboratory Measurements	M. Kurylo	453-1681
Interdisciplinary Research	W. Huntress	453-1707
Applications/Commercialization Program	W. Huntress	453-1700
Aircraft Program	W. Huntress	453-1700
EOS	D. Butler	453-1681
Geoplatform	J. Dodge	453-1680
Space Flight Programs	W. Townsend	453-1725
METSAT Development Ops	J. Greaves	453-1723
Shuttle Payloads/Ext. Ops	G. Esenwein	453-1723
SAR/HIRIS	R. Monson	453-1723
Satellite Development		
UARS	M. Luther	453-1723
TOPEX/NSCAT	L. Jones	453-1725
Earth Probes Planning	D. Butler	453-1681
Space Station Planning		
EOS/Attached Payloads	A. Tuyahov	453-1723

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It is expected that the first four polar platforms will carry as many as 50 instruments. These include NASA research facility instruments and instruments being developed by investigators selected by NASA early in 1989 in response to the Announcement of Opportunity released in 1988. Other instruments will be supplied by Japan, ESA, several individual European countries, Australia, and selected NASA instrument investigators. NOAA and other operational entities also plan to provide a set of operational facility instruments. More details on these instruments and the investigations for which they will be used are given in Chapter 2.

A highly complex and technologically advanced data and information system, EOSDIS, is being developed to process the unprecedented amount

TABLE 1-2. **CHANGES IN FLIGHT MISSION SCHEDULES**

Mission	Previous Schedule	Proposed Current Schedule
LOW EARTH ORBIT		
UARS	Fall 1991	November 1991
TOPEX/POSEIDON	December 1991	June 1992
NASA Scatterometer/TOMS (ADEOS)	June 1994	February 1995
TOMS (Meteor-3)	—	Fall 1991
Earth Observing System (EOS)	Late 1996	Late 1997
SHUTTLE MISSIONS & INSTRUMENTS		
Shuttle Solar Backscatter Ultraviolet Spectrometer (SSBUV)/1	February 1989	October 1989
ATLAS-1	Fall 1990	March 1991
SIR-C	mid-1991	June 1992

and variety of data that will flow from the spaceborne EOS instruments, and to distribute them rapidly to the Earth science community worldwide. NASA is developing EOSDIS in close cooperation with NOAA, other federal agencies, and EOS international partners. Data available to EOS investigators will range from short browse data sets to entire global data sets from a wide range of spaceborne and ground-based instruments.

In preparation for EOSDIS, ESAD has established an Earth Science and Applications Data System (ESADS) to integrate the most effective elements of its current data systems and data processing and distribution activities. EOSDIS will build on the experiences of successful ESADS prototypes as these mature and are evaluated by the science community. As an example, a special computerized interactive data network, WetNet, is being developed in order to link scientists at NASA and universities in the United States and other countries who are involved in studies of the hydrological cycle. Beginning in 1990, WetNet participants will have daily access to data from the spaceborne Special Sensor Microwave Imager (SSM/I) in order to exchange ideas and information and conduct interdisciplinary research. WetNet will serve as a useful prototype for EOSDIS in preparing for truly interdisciplinary cooperation among disparate scientific groups. Other prototype examples are data systems such as the NASA Ocean Data System, NASA Climate Data System, Pilot Land Data System, and retrospective processing activities such as the Coastal Zone Color Scanner (CZCS) global chlorophyll data set.

Data system planning is coordinated with other federal agencies through the Interagency Working Group on Data Management for Global Change (IWGDMGC) involving NASA, NOAA, NSF, the U.S. Navy, the U.S. Departments of Energy and Agriculture, and international groups such as the Committee on Earth Observation Satellites (CEOS) to coordinate data and information systems.

In all, EOS has the potential to provide many important breakthroughs in our scientific understanding of a wide range of single discipline and multidisciplinary Earth science problems.

Earth Probes

EOS investigations will be complemented and extended by those of the Earth Probes—the Earth Explorer mission series of smaller, specialized U.S. satellites, which will be launched before and during the 15-year EOS space flight period. Instruments on Earth Probe satellites will be used for investigations requiring low equatorial orbits as opposed to the sun-synchronous polar orbits of the large EOS platforms. Earth Probes will study such phenomena as the thermosphere, the Earth's gravitational and magnetic fields, rainfall, and ozone depletion. Proposed missions include the Tropical Rainfall Measuring Mission (TRMM) in collaboration with Japan; gravity gradiometer missions; the Magnetic Field

Explorer (MFE) mission with France; and the Total Ozone Mapping Spectrometer (TOMS). A new TOMS will be flown on a Scout-launched spacecraft in January 1993 as part of this small Earth Explorer mission series.

Agreement has been reached between U.S. and Soviet space officials to fly a TOMS on a Soviet Meteor-3 weather satellite scheduled for launching in the fall of 1991. The TOMS has also been selected, along with the NASA Scatterometer (NSCAT), for inclusion in Japan's Advanced Earth Observing Satellite (ADEOS) study. The launch of ADEOS is planned for early 1995.

The TOMS instrument has already made a significant contribution toward our knowledge of atmospheric ozone depletion. Since 1978, a TOMS on the Nimbus-7 satellite has provided key global measurements of atmospheric ozone—far exceeding its design life. Moreover, TOMS measurements confirmed the existence of the large ozone hole over Antarctica, reported by the British Antarctic Survey in 1985.

Space Station Attached Payloads

The Space Station Freedom (SSF) will fly in a low inclination (28.5°) and at low altitude (400 km) and will provide information on the diurnal cycle. The low inclination will concentrate measurements on the equatorial region, the most dynamic region of the planet. The selection of several EOS instruments for flight as Space Station Attached Payloads was announced in June 1989. Some of these instruments will be developed as SSF Attached Payloads only, while others will be modified copies of instruments being developed for flight on the NASA polar platforms.

Attached payloads will be flown in two distinct phases. Instruments planned for flight during the first construction phase of the SSF include CERES (a pair of broadband, scanning radiometers to provide data on clouds and the Earth's radiation budget; the Stratospheric Aerosol and Gas Experiment III (SAGE III); and the Lightning Image Sensor (LIS). Instruments that will be considered for later flights (i.e., after 2003) include the Moderate-Resolution Imaging Spectrometers (MODIS-N and MODIS-T); the Rain Radar; the High Resolution Microwave Spectrometer Sounder (HIMSS); the GPS Geoscience Instrument (GGI); and the Advanced Scatterometer for Studies in Meteorology and Oceanography (SCANSAT). These instruments are described in more detail in Chapter 2.

Geostationary Platforms

Mission to Planet Earth requires the development and deployment of five geostationary platforms in order to attain observations of those physical processes that begin and evolve significantly within the course of a day. The fleet of EOS polar-orbiting platforms can only provide a snapshot of such processes, a snapshot which may have changed considerably by the time of the next satellite overpass. Data on these short-term physical processes will be used in numerical models to relate the polar-orbiter measurements to a projection of future climate change potentials.

The Science Steering Committee for the Earth Science Geostationary Platform (GEO) has determined a set of observing objectives that is appropriate for the geostationary perspective. It includes fast atmospheric processes such as precipitation, lightning, rapid thermodynamic structure changes, and transient observable features such as clouds, fog, and dust storms. The required objectives also include fast coastal changes and land surface interactions produced by flooding and tidal wetland changes. Biologists wish to monitor ocean productivity variability and diurnal changes in ecosystem stress. Others wish to use the constant viewing potential of a geostationary platform to monitor the Earth's radiation budget and subtle total and spectral solar irradiance variations. Still other scientists wish to use the "constant eye" of the geoplatform to detect volcanic eruptions, specify their gas emissions, and try to estimate the composition of eruptive volcanic materials (tephra) through changes in color. The atmospheric chemists want to monitor the variability of air pollution composition and to be able to map the progress of aerosol and haze plumes.

In June 1988 six facility instruments that best complemented the proposed EOS instruments and best met the multidisciplinary requirements of the GEO mission were selected for Phase A study, for their ability, for example, to make the required observations at the orbital altitude of a geostationary satellite. The instrument types were chosen to parallel, as far as possible, certain important instruments on the EOS polar platforms in order to make direct intercomparisons and to allow the geostationary observations to characterize the needed diurnal variability that will permit the most accurate interpretation of the EOS data.

The instruments under study include a microwave imager/sounder, a moderate-resolution imaging spectrometer, a high resolution interferometric imaging spectrometer, a lightning mapper, a high resolution multispectral imager for special localized observations, an Earth radiation budget sensor, and solar irradiance sensors. Figure 1-2 shows one current GEO platform concept. Additional sensors could result from successful proposals in response to an Announcement of Opportunity which will be issued in the next couple of years. In addition, the initial platform and data system requirements are being developed for future detailed configuration studies. The data handling pre-processing, distributing, and integrated product browsing problem will be given heavy emphasis, since efficient and easy access to the GEO and EOS data is essential in order to reap the maximum reward from Mission to Planet Earth. The GEO component of Mission to Planet Earth is planned for flight around the turn of the century.

Other Highlights of 1989

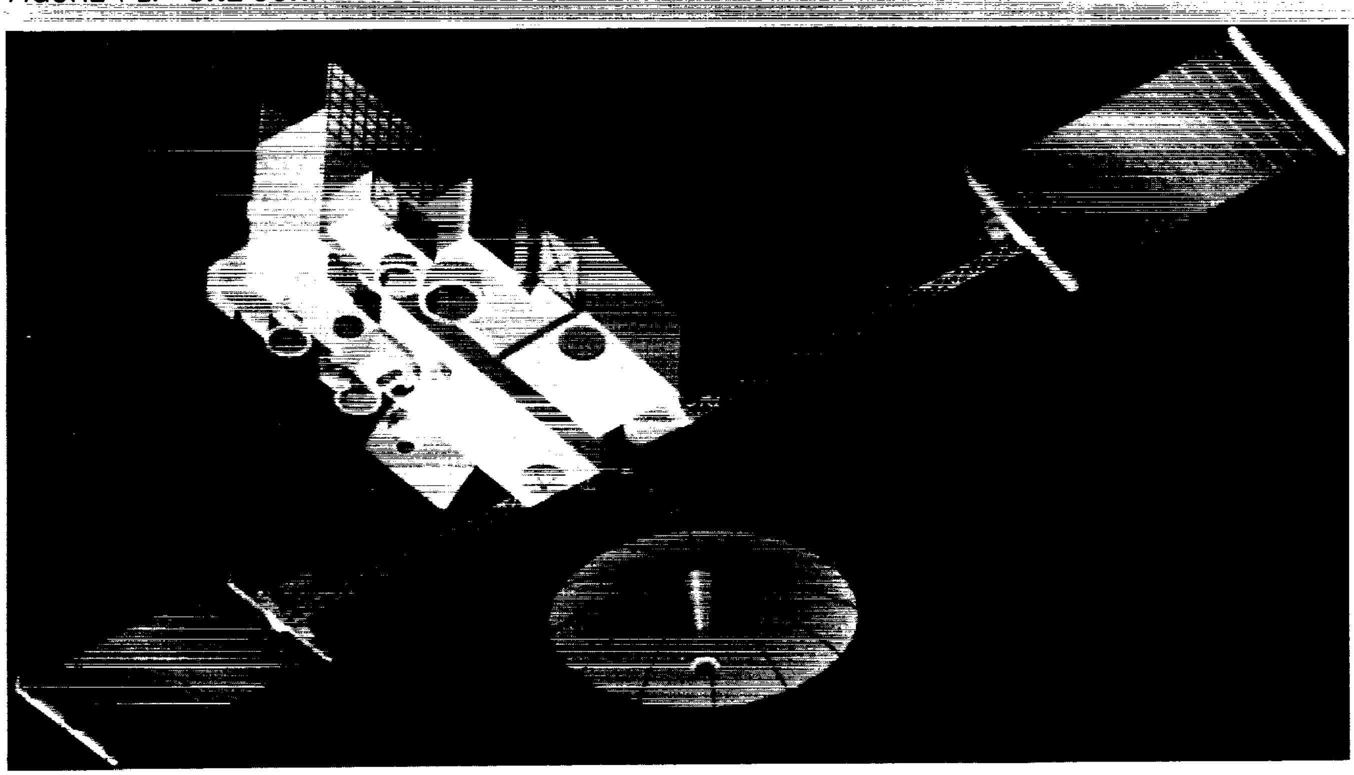
Studies of Ozone Depletion

Studies by NASA, NOAA, and other federal science agencies have greatly increased our understanding of global ozone depletion. In early 1989, NASA and NOAA jointly coordinated a 6-week Airborne Arctic Stratospheric Expedition to study stratospheric chemistry and meteorology over the Arctic, described in more detail later in this report. This expedition was a follow-on to a similar aircraft study in 1987 of ozone loss in Antarctica. (While further analysis is needed for a fully quantitative understanding of the exact mechanisms responsible for this Antarctic ozone loss, observational evidence implicates both man-made chlorofluorocarbons and meteorological processes, i.e., the combination of extremely low temperatures, the presence of polar stratospheric clouds [PSCs], and the return of sunlight to generate the chemical reactions that enhance the buildup of reactive chlorine compounds, resulting in ozone destruction.)

The Arctic Expedition took place during early winter when polar stratospheric clouds are most likely to form. Between January 1 and February 15, 1989, NASA ER-2 and DC-8 aircraft carrying many of the same instruments as used in the Antarctic, flew 28 missions over the Arctic as far as the North Pole to investigate the chemical and dynamical processes that control ozone in the Arctic polar stratosphere.

Preliminary results from this study indicate that the chemical composition of the Arctic polar stratosphere is highly perturbed and that these perturbations occur over a wide range of altitudes in the stratosphere. In the Antarctic, significant ozone depletion takes place following chemical reactions

FIGURE 1-2. **ONE CURRENT GEO PLATFORM CONCEPT**



occurring on the PSCs and the return of sunlight. Any ozone loss in the Arctic is expected to be much less because chemical perturbations are not as severe, long-lasting, or spatially extensive as they are in the Antarctic. The Antarctic stratospheric circulation is driven more radiatively than in the Arctic, resulting in significantly colder temperatures in the lower stratosphere, more PSCs, and a much stronger west to east jet stream than in the north. In both regions, there is evidence for a PSC-induced chemistry which enhances the buildup of active chlorine. This heterogeneous chemistry was not included in the stratospheric ozone assessment models used as the basis for the Montreal Protocol and has been strongly implicated in the Antarctic ozone loss. While no large ozone losses have been observed in the Arctic, strong perturbations in active chlorine were observed.

A more complete assessment of the scientific data from the Arctic mission will be released in February 1990 with publication of the data and scientific papers by individual researchers involved in the mission.

Earth Radiation Budget

Earth Radiation Budget Experiment (ERBE) investigations are beginning to provide valuable new insights into the Earth's radiation budget and the important climatic effects of clouds as they modulate (block) radiation from both the Sun and the Earth. One ERBE study has found that, at present, clouds cool the Earth's climate below the temperature it would be without clouds. This is because the cooling effect of blocked incoming solar radiation is greater than the warming greenhouse effect caused by blocking outgoing Earth-emitted radiation. Current evidence suggests that this situation may not last if global warming from increased greenhouse emissions continues, although more studies are necessary to verify this prediction.

Since 1984, data from instruments aboard three spacecraft, the NOAA-F and NOAA-G TIROS-class operational meteorological satellites and NASA's Earth Radiation Budget Satellite (ERBS), are helping researchers to develop more realistic models for predicting global climatic change that recognize the highly complex feedback mechanisms involved in the interactions between clouds, the radiation balance and other natural processes, and human activities. In addition, investigators have discovered that changes in cloudiness, even as small as 1-2 percent, could produce far more significant transformations in the Earth's climate than currently predicted increased greenhouse gas emissions.

Cloud Climatology

This year, the International Satellite Cloud Climatology Project (ISCCP), the first project of the World Climate Research Program, completed its 7th year of data collection. For the first time, a calibration standard for visible and infrared imaging data now exists for the quantification of information on clouds in long-term climate monitoring and analysis. The ISCCP cloud analysis procedure is the first comprehensive multidata analysis system ever implemented, making it possible to combine data from imaging, temperature/humidity profiles, and worldwide conventional weather observations into a single global analysis.

Building on this achievement, a major ISCCP program, Project FIRE (First ISCCP Regional Experiment) has, since 1984, been collecting an unprecedented amount of data on the radiative and physical properties of two types of clouds that have a significant impact on the Earth's climate: cirrus and marine stratocumulus. Analyses of these measurements were presented at the July 11-15, 1988 FIRE Science Workshop in Vail, Colorado. These analyses have yielded more accurate breakdowns of the components of these two types of clouds and more information on the effects of solar radiation reflectivity from marine stratocumulus clouds. For example, investigators found that broken clouds reflect 12 percent less solar radiation than solid overcast ones.

Further studies of cirrus and marine stratocumulus clouds are planned for the early 1990s. These include a cirrus cloud experiment in Kansas; a tropical cirrus cloud experiment near Kwajalein, Marshall Islands; and the Atlantic Stratocumulus Transition Experiment (ASTEX) near the Azore Islands.

Solid Earth Sciences

At a meeting held by NASA in July 1989 at Coolfont, West Virginia, over 100 scientists developed a proposed integrated research plan which would combine NASA's previously autonomous Geology and Geodynamics Programs into a single Solid Earth Science Program responsive to the needs of international global change research.

Five high-priority research or mission targets emerged which address the interdisciplinary requirements of Earth sciences including geology and geophysics, hydrology, ecology, and climatology. The scope of the effort would be very great, and substantial domestic interagency and international cooperation will be essential to fulfill all ambitions. The new research areas recommended by the meeting are:

- A Global Geophysical Network of 200 continuously monitored space geodetic stations capable of measuring global motions to millimeter position accuracy, and to be called the Fiducial Laboratory for an International Natural Science Network (FLINN), in honor of the pioneering work of Dr. Edward A. Flinn in crustal dynamics
- Global topographic mapping through remote sensing from space
- A study of soils and surface processes to understand how the land surface changes under natural and anthropogenic influences and the nature and rate of global change over periods from months to decades
- Improvements in capability to measure and understand the gravity and magnetic fields of the Earth
- The further investigation of volcanic effects of climate through the study of the origins of volcanic gases and aerosols; their transport, residence time, and reactions; and the modeling of the climate effects of these influences

Much activity is now being devoted to the further definition of the collaboration across agencies and between international partners required to design and coordinate the implementation of this new direction for Solid Earth Science.

Current Flight Programs

Mission to Planet Earth will be built upon the foundation of current research and operational activities. Current NASA space missions continue to produce important new findings about the Earth's atmosphere, climate, geological processes, and oceans. The Division is now engaged in the development of the Upper Atmosphere Research Satellite (UARS), TOPEX/POSEIDON, and the Scatterometer (NSCAT), all due for launch within the next 3 to 5 years.

Nimbus-7. Nimbus-7 continues to provide significant quantities of global data on sea-ice coverage, atmospheric temperature, ozone distribution, the Earth's radiation budget, and sea surface temperature. Three of its seven instruments still operate: the Solar Backscatter Ultraviolet/Total Ozone Mapping Spectrometer (SBUV-TOMS), the Stratospheric Aerosol Management II (SAM II), and the Earth Radiation Budget (ERB) instrument.

Strong demand exists for the Nimbus-7 data, which are used to study global weather trends and Earth climate, to analyze and predict severe storms and ozone concentration trends, and to improve numerical forecast models.

Options are being considered for replacing the Nimbus-7 TOMS instrument which, operating since 1978, has far exceeded its design life. The new TOMS instrument will obtain almost global daily ozone maps, taking some 200,000 measurements each day, of all sunlit areas. Only those areas experiencing polar night will not be observed. It is proposed to fly a new TOMS on a Soviet Meteor-3 satellite planned for launch in the fall of 1991. More details of this mission can be found in Chapter 4. Another option would be to launch a new TOMS on a Scout vehicle in 1993 as part of the small Earth Explorer mission series. This instrument has also been selected as a potential candidate for the Japanese Advanced Earth Observing Satellite (ADEOS) to be launched in early 1995.

Earth Radiation Budget Experiment (ERBE). This experiment measures variations in the Earth radiation budget over time and space to gain basic insight into the causes of climatic fluctuations. For adequate global coverage, three identical instruments are flying on the NOAA-9 and -10 satellites and on a dedicated NASA observatory called the Earth Radiation Budget Satellite (ERBS). The ERBS also carries the Stratospheric Aerosol and Gas Experiment (SAGE II) to measure ozone, water vapor, nitrogen dioxide, and aerosols.

Upper Atmosphere Research Satellite (UARS). The UARS, currently scheduled for launch on a space Shuttle in November 1991, will undertake the first systematic study of the stratosphere in order to obtain new information on the mesosphere and thermosphere. Nine sensors on the UARS will provide the most complete data ever gathered on atmospheric energy inputs, winds, and chemical composition. The findings of the UARS study will help reveal the mechanisms that control the structure and variability of the upper atmosphere, improve the predictability of ozone depletion, and define the impact of the upper atmosphere on the Earth's climate. Great Britain and Canada are contributing toward the development of UARS instruments, and scientists from many countries will eventually participate in the analysis and use of UARS data.

TOPEX/POSEIDON. The Franco-U.S. 3-year TOPEX/POSEIDON mission will map the circulation of the world's oceans from detailed measurements of the sea surface topography. This mission, in combination with NSCAT, will be able to provide the global description of ocean circulation necessary for improved climate prediction models. TOPEX/POSEIDON is scheduled for a June 1992 launch on France's Ariane satellite and an international team of 38 principal investigators has been selected to conduct TOPEX/POSEIDON investigations.

NASA Scatterometer (NSCAT). Work is also continuing on NSCAT, an ocean-wind-measuring radar instrument which will collect detailed global data on near-surface ocean winds. This instrument, which is being studied for flight on ADEOS, will provide frequent measurements of oceanic near-surface vector winds with high spatial resolution and global coverage. Both TOPEX/POSEIDON and NSCAT are critical components of the World Ocean Circulation Experiment (WOCE) and the Tropical Oceans Global Atmosphere Experiment (TOGA) of the World Climate Research Program. These missions will make an important contribution toward meeting the goals of these international organizations.

The Atmospheric Laboratory for Applications and Science (ATLAS). The ATLAS mission will measure solar radiation and properties of the upper atmosphere through a series of once-a-year flights beginning in March 1991. The first in this series, ATLAS-1, will fly on a dedicated Shuttle mission, and the second and third, ATLAS-2 and ATLAS-3, planned for launch in the summer of 1992 and in 1993, respectively, will underfly the UARS in order to make correlative atmospheric measurements with that satellite's instruments.

Solar Irradiance Monitoring Program. The goal of the Solar Irradiance Monitoring Program is to produce a continuous, long-term solar constant data base with sufficient precision for climatological studies. Missions flying solar constant instruments must overlap to provide continuous data sets. An Active Cavity Radiometer Irradiance Monitor (ACRIM I) is now flying on the Solar Maximum Mission, and ACRIM II is planned for flight on the UARS. It is hoped that ACRIM instruments can be placed on a NOAA GOES, because this spacecraft's geosynchronous orbit would provide almost 100 percent continuous solar observation.

Shuttle Solar Backscatter Ultraviolet Spectrometer (SSBUV). The SSBUV is being readied for flight in October 1989, along with the Galileo launch, with flights scheduled about one a year, from 1990 through to 1997, when the EOS space flight program begins. This instrument will be used to help calibrate existing SBUV ozone sensors on the Nimbus-7 satellite and NOAA weather satellites.

Lightning Mapper Sensor (LMS). Measurements of lightning flashes during both day and night will be provided by the Lightning Mapper Sensor (LMS), proposed for flight aboard the NOAA GOES series. Observations by this instrument will yield new insights on lightning in relation to the evolution of storms, the formation of clouds, and precipitation. (The Lightning Imaging Sensor [LIS] selected by NASA for EOS instrument investigations and scheduled to fly on the first NASA EOS platform, will trace and investigate the distribution and variability of lightning over the Earth. This instrument will provide important information for EOS studies because lightning activity is linked to storm convection, dynamics, and microphysics , and can be correlated to the global rates, amounts, and distribution of precipitation.)

Coastal Zone Color Scanner (CZCS). Recently published data from satellite observations by the Nimbus-7 Coastal Zone Color Scanner (CZCS) have provided the Earth science community with its first comprehensive global view of oceanic productivity. Biological oceanography has been revolutionized by these observations, which revealed the spring blooming of the North Atlantic, the extent of the equatorial enrichment of productivity, and the dynamics of coastal oceanic processes. Data from the CZCS sensor suite represent 7 years of data collection, and have been essential to the planning and implementation of the Joint Global Ocean Flux Study, an international effort to understand how oceans influence global biogeochemical cycles, and thus the Earth's future climate.

The Laser Geodynamics Satellite (LAGEOS)-2. LAGEOS-2, developed jointly by the United States and Italy, has been delivered to Goddard Space Flight Center in Greenbelt, Maryland for characterization tests. LAGEOS-2 will be used for precise geodetic positioning, and is scheduled to fly on the Italian IRIS upper-stage launch vehicle that will be placed in orbit by the Shuttle in September 1991. LAGEOS-3, currently under study, could be placed in an orbit that would increase the complement of satellites available for geodynamic laser ranging and provide important data for relativistic physics.

2

The Earth Observing System

The Earth Observing System, EOS, is an internationally coordinated, multidisciplinary spaceborne observation program of the 1990s that will study interactions among Earth's land, sea, and atmosphere, and document changes in the global environment. This program is the centerpiece of NASA's Mission to Planet Earth, which aims to obtain a scientific understanding of the entire Earth as an integrated system and to determine the processes that contribute toward environmental balance or change. Mission to Planet Earth also addresses the major environmental issues of global warming, ozone depletion, tropical deforestation, and desertification. The program will help scientists to develop the capability to predict the changes that will occur over time scales of 10 to 100 years as a result of either natural phenomena or human activity, and to acquire and analyze scientific information that could influence U.S. and international environmental policies for the benefit of mankind.

The EOS mission will create a unified scientific observing system that will permit interdisciplinary and multidisciplinary studies of the Earth's atmosphere, biosphere, oceans, land surfaces, polar regions, and the solid Earth. EOS will provide:

- The first global observations on the ways in which human, animal, and plant life interact with the planet and affect its natural processes; and
- The first coordinated measurements of Earth as a complex system of interactions among solar energy, land, sea, and air.

The Program

The EOS program will provide a crucial information resource for the international scientific community and its unique benefits will be made available to all who want to participate.

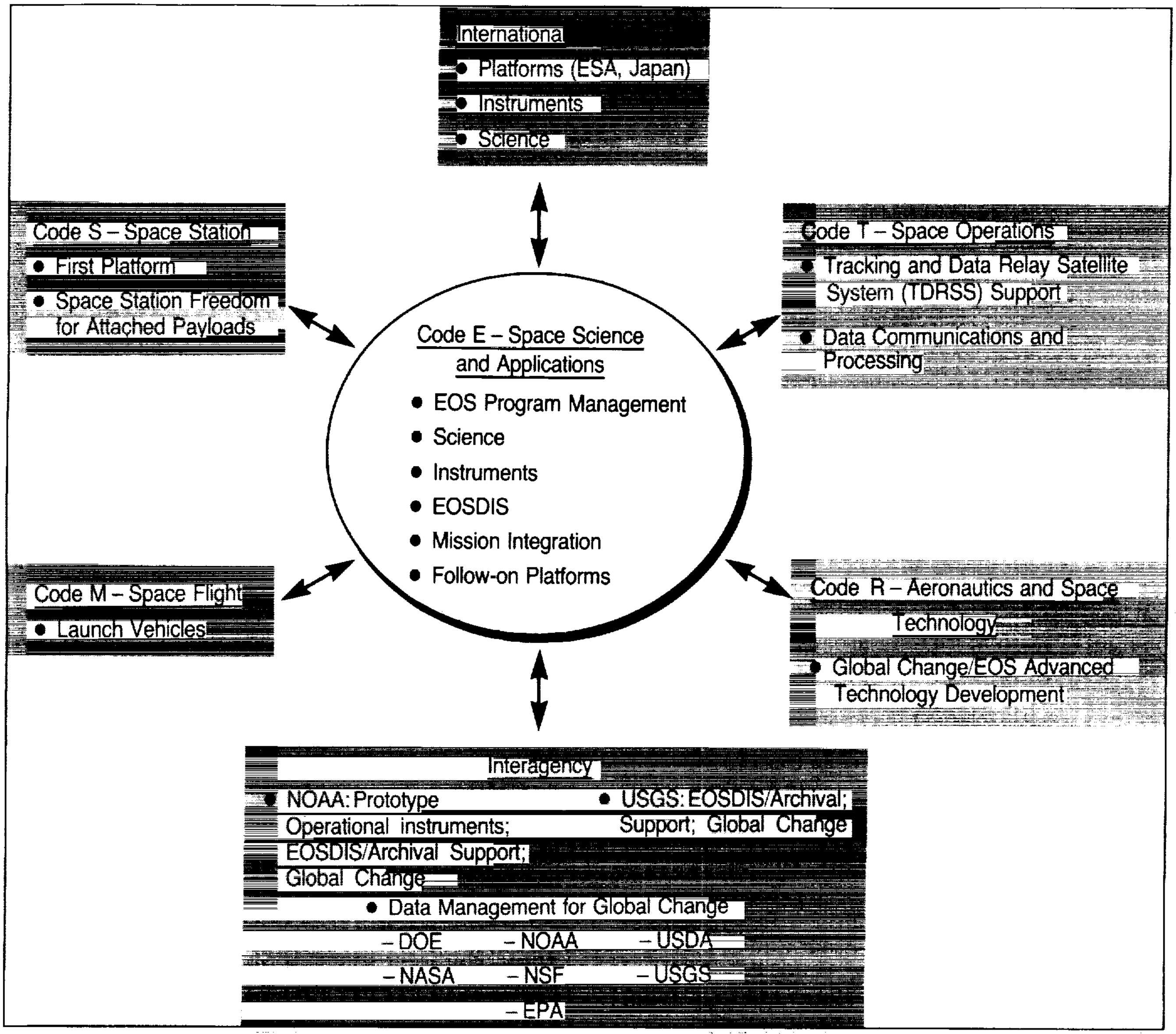
EOS will be operated by NASA in conjunction with the National Oceanic and Atmospheric Administration (NOAA) polar operational program and in cooperation with the three Space Station partners: the European Space Agency (ESA), Japan (Science and Technology Agency [STA] and National Space Development Agency [NASDA]), and Canada. In addition, representatives of the operational organizations, i.e., NOAA (United States), EUMETSAT (Europe), JMA (Japan), and the Department of the Environment (Canada) are also participating in the coordination of EOS, in particular, the use of polar platforms for Earth observations. Figure 2-1 depicts the programmatic interfaces to EOS.

Beginning in 1997, a series of large polar orbiting space platforms will be launched over a 15-year time scale. Each platform will enable a greater number and variety of instruments to gather data simultaneously as it circles the Earth, thus significantly expanding research opportunities and capabilities. These and later series of platforms will carry both research and operational instruments, thereby providing Earth science investigators with the long-term, consistent data sets necessary for understanding and predicting global processes.

The first NASA EOS platform is part of the Freedom Space Station Program which will operate a permanently manned research laboratory with crews from the participating countries. As an important component of Mission to Planet Earth, the Space Station, also carrying instruments for EOS investigations, will increase scientific knowledge of the Earth as an interrelated system, and stimulate both the development of new technologies and the exploration of the commercial potentials of space.

During the first 5 years of the EOS program, five large, unmanned polar platforms carrying remote-sensing instruments are now proposed for launching as follows:

FIGURE 2-1. **EOS PROGRAMMATIC INTERFACES**



March 1997 – European Space Agency Platform (EPOP-1A)
December 1997 – NASA Polar Orbiting Platform (NPOP-1 [EOS-A])
1998 – Japanese Polar Orbiting Platform (JPOP)
December 1999 – NASA Polar Orbiting Platform (NPOP-2 [EOS-B])
2000 – European Space Agency Platform (EPOP-1B)

ESA plans to launch two series of at least three platforms each, beginning with Series A and B shown above, because its spacecraft will need to be replaced about every 5 years for the duration of EOS. For the same reason, NASA plans to launch two series of three platforms each, beginning with EOS-A and EOS-B, and continuing with the first series in 2001 and 2006 and the second series in 2003 and 2008. Table 2-1 shows EOS milestones to the year 2000.

The international cooperation that EOS will entail is evidenced by the number of remote-sensing instruments being contributed by many different countries to fly on other than "national" platforms. Instruments aboard EOS-A and EOS-B will include ones developed by NASA, by teams of investigators (from the United States and overseas) selected by NASA; and by Canada, ESA, France, and the Ger-

TABLE 2-1. **FUTURE EOS MILESTONES**

1990	February	Instrument execution-phase: Conceptual Design and Cost Reviews
	March	Interdisciplinary Investigation Performance Reviews
	September	Final selection of instruments for first NASA-supplied platform payload: Confirmation of all other definition-phase selections
1991	January	Initiation of payload execution phase
1995	January	Delivery of instruments to NASA for integration on first NASA-supplied polar platform
1997	March	Launch of ESA-supplied platform
1997	December	Earliest possible launch of first NASA-supplied polar platform
1995-97		Launch of instruments as attached payloads on the manned Space Station
1998		Launch of Japanese-supplied platform
1999	December	Earliest possible launch of second NASA-supplied polar platform

man Federal Republic. The ESA-A platform will carry European, Japanese, and Australian Earth and atmospheric sensors, and a U.S. Earth Radiation Budget sensor. The U.S. Laser Atmospheric Wind Sounder (LAWS) is planned for Japan's platform (JPOP) along with five other Japanese-developed instruments.

In addition, NASA and NOAA have recommended an operational instrument space flight plan for EOS in which core meteorological payloads will fly on NOAA free flyers and ESA series A platforms. These operational core payloads would include instruments for imaging, sounding, ozone monitoring, and search and rescue.

Under the proposed NASA-NOAA plan, NASA platforms would carry a combined EOS research and prototype operational payload. The prototype operational instruments which would be developed by NASA would include those for monitoring wind speed and direction over the oceans (Scatterometer), ocean wave height and circulation (Altimeter), Earth radiation budget (ERBI), and advanced infrared soundings (AIRS—one of the NASA facility instruments).

Also, NOAA and other operational entities plan to provide a set of operational facility instruments including the Advanced Microwave Sounding Unit (AMSU) for measuring atmospheric temperature and humidity; the Advanced Medium Resolution Imaging Radiometer (AMRIR); the Global Ozone Monitoring Radiometer (GOMR); and the Space Environment Monitor (SEM). Figure 2-2 gives an overview of the scentific investigations currently planned for the EOS flight missions.

The anticipated duration of EOS is 25 years, with authorization anticipated for a New Start in FY 1991. During the following 15-year space flight part of the EOS program, instruments on the space platforms will provide continuous low-Earth orbit observations of Earth system components in order to monitor their interactions and long-term processes of global change. Scientific analyses of data from these spaceborne instruments, from associated ones on the ground, and from studies based on these data, will be finalized during the last 5 years of EOS.

EOS Investigations

An important stage of the EOS Program was completed in February 1989 when NASA finalized the selection of scientific investigations for EOS. The teams of researchers for the selected projects consist of 551 individuals from 168 institutions, universities, and laboratories in 32 states and 13 countries including the United States.

Of the 455 proposals received, NASA chose the following:

- Six facility instrument investigations (research and operational instruments developed by one of the NASA facilities, e.g., the Jet Propulsion Laboratory) involving over 75 team members in all
- Twenty-four instrument investigations involving principal and co-investigators from the United States and elsewhere
- Interdisciplinary studies by 28 investigators (20 United States investigators and 8 from other countries)

NASA had solicited proposals for these investigations in its Announcement of Opportunity (AO), released in January 1988. At the same time, concurrent AOs were issued by ESA soliciting payload

FIGURE 2-2. **OVERVIEW OF EOS SCIENCE INVESTIGATIONS**

	NASA POLAR PLATFORM 1 705 KM EOS A (U.S.A.)	NOAA FREE-FLYER 824 KM (U.S.A.)	SOLAR FLIGHT OF OPPPORTUNITY (U.S.A.)	SPACE STATION ATTACHED PAYLOADS 400 KM (U.S.A)	NASA POLAR PLATFORM 2 705 KM EOS-B (U.S.A.)	ESA POLAR PLATFORM 1 (EPOP-A) 824 KM (ESA)	ESA POLAR PLATFORM 2 (EPOP-B) 705 KM (ESA)	JAPANESE POLAR PLATFORM (JPOP) 800 KM (JAPAN)
METEOROLOGICAL OBSERVATIONS, WEATHER	●	●				●		
STORM MONITORING & WARNING		●				●		
SEARCH & RESCUE		●				●		
ORBIT DETERMINATION	●				●	●		
INTERIOR EARTH STRUCTURE					●			
PLATE MOTION & CRUSTAL DEFORMATION	●				●	●		
SURFACE SOIL MOISTURE, WETLANDS EXTENT	●			●		●	●	
LAND SURFACE COMPOSITIONI	●			●		●	●	●
LAND SURFACE BIOLOGICAL ACTIVITY, PHENOLOGY & PHYSIOLOGICAL STATE	●			●		●	●	●
SURFACE TOPOGRAPHY	●					●	●	
SURFACE TEMPERATURE	●	●		●	●	●	●	●
SNOW & ICE EXTENT/CHARACTER	●	●		●		●	●	●
SEA ICE EXTENT, CHARACTER, & MOTION	●	●		●		●	●	●
SEA SURFACE WINDS	●			●		●	●	●
OCEAN WAVES					●	●		
OCEAN CIRCULATION				●	●	●		
OCEANS & LAKES BIOLOGICAL ACTIVITY	●			●		●		
AEROSOLS	●				●			●
TROPOSHERIC WINDS						●	●	●
TROPOSHERIC COMPOSITION	●			●	●	●	●	
CLOUD PROPERTIES	●	●		●	●	●	●	
ATMOSPHERIC TEMPERATURE	●	●		●	●	●	●	
ATMOSPHERIC WATER CONTENT	●	●		●	●	●	●	●
PRECIPITATION RATE	●			●		●	●	●
LIGHTNING	●			●				
UPPER ATMOSPHERIC WINDS	●				●			
UPPER ATMOSPHERIC COMPOSITION	●	●			●		●	
PARTICLES & FIELDS ENVIRONMENT	●	●			●	●		
IONOSPHERE	●				●			
EARTH RADIATIVE BUDGET	●	●		●		●		
SOLAR OUTPUT	●	●	●					

Based on a chart compiled by Hughes-Santa Barbara Research Center development for the European Polar Platform and by the Japanese for use of the data from their instruments aboard the Space Station Platform.

Research Facility Instrument Investigations will analyze data from the NASA research facility instruments aboard the space platforms. Team leaders and members will also participate in the development of these instruments:

- ***Atmospheric Infrared Sounder (AIRS)***—to measure atmospheric temperature, moisture, and other properties as a function of height above the ground with an accuracy and resolution far surpassing current operational satellite instruments.

- ***Geoscience Laser Ranging System (GLRS)***—to study the Earth's crustal movements in earthquake-prone regions and across tectonic plate boundaries by precisely determining the locations of special mirrors set up on the ground. This instrument could represent a step toward earthquake prediction. GLRS can also measure the surface height profile of glaciers and polar ice sheets to determine how fast they are growing or shrinking.

- ***High Resolution Imaging Spectrometer (HIRIS)***—to provide highly programmable, localized measurements of geological, biological, and physical processes of the Earth system. HIRIS will be used to enable investigators to interpret properties of the Earth's surface at a level of detail unmatched by any previously developed spaceborne instrument.

- ***Laser Atmospheric Wind Sounder (LAWS)***—a laser detection and ranging system for measuring low altitude wind velocities by observing the Doppler shift in light reflected from windborne dust. This instrument should improve wind speed measurement at low altitudes.

- ***Moderate Resolution Imaging Spectrometer (MODIS-T/-N)***—to measure biological and physical processes in the study of terrestrial, oceanic, and atmospheric phenomena. This instrument is being designed to observe the changes in the Earth's biology which accompany seasonal change, to monitor the temperature structure of the atmosphere, and the thermal changes in the sea's surface.

- ***Altimeter (ALT)***—a microwave altimeter to measure ocean circulation and variability and sea surface winds and waves.

The decision was made in 1988 that NASA rather than NOAA, would provide the EOS altimeter as a facility instrument. The instrument will be a TOPEX class altimeter with measurement capabilities very similar to TOPEX, such as dual frequencies and the same 1–2 cm order of precision. The TOPEX/POSEIDON science team was invited to form an interim science working team to begin the definition of science requirements for the EOS Altimeter. It is expected that an Announcement of Opportunity for EOS altimeter investigations will be made after the launch of TOPEX/POSEIDON in mid-1992. The polar-orbiting, low altitude EOS platform will offer altimeter investigators the opportunity for glacial and other high latitude studies which the TOPEX/POSEIDON orbit (63°) will not provide. A Synthetic Aperture Radar (SAR) was initially selected as a research facility instrument in February 1989. However, as a result of the June Non-Advocacy Review (NAR) this instrument has been deferred from the anticipated FY 1991 New Start to a future year budget initiative.

Details on the research facility instrument investigations are given in Table 2-2.

Japanese and European research facility instruments will fly on the NASA platforms. Japan is developing the Intermediate and Thermal Infrared Radiometer (ITIR) which will measure land surface composition, biological activity, and changes in organisms due to climate. ESA's facility instruments include the Moderate Resolution Imaging Spectrometer (MERIS) for global ocean color monitoring; the High Resolution Imaging Spectrometer (HRIS) for land and coastal investigations; an Atmospheric Lidar (ATLID) for atmospheric research and pre-operational meterology; a Wind Scatterometer (SCATT-2); a Radar Altimeter (ALT-2); and a C-Band Synthetic Aperture Radar (SAR-C).

Instrument investigations involve both the development of scientific instruments for flight on the polar platforms and analyses of resulting data. These investigations will produce important new findings on the Earth system, and in some cases, on space physics phenomena. Investigators have designed a variety of sensors, particularly radiometers and spectrometers, capable of gathering accurate information on features of the Earth system components (see Table 2-3). These instruments will investigate such phenomena as solar and Earth radiation; the natural and anthropogenic chemical composition of the atmosphere; the effects of geophysical processes and human activities on the Earth's ecology and climate; the speed and direction of surface winds over tropical oceans under all weather conditions; cloud properties; and the Earth's magnetic field.

TABLE 2-2. **INVESTIGATIONS USING NASA RESEARCH FACILITY INSTRUMENTS**

Atmospheric Infrared Sounder (AIRS)
Team Leader, Dr. Moustafa Chahine, JPL

- Radiative Interactions in Cloudy Atmospheres
- Spatial and Temporal Extent of Sea Surface Temperature Abnormalities and Climate Correlations
- Forward and Inverse Radiative Transfer Modeling
- Retrieval Algorithm Development
- Calibration and Ocean Surface Radiation Budget Computations
- Processing and Validation of AIRS Data and Its Impact on Mesoscale Analysis and Prediction
- Algorithms for Validating and Tuning AIRS Measurements
- Evaluation of the Utility of AIRS Data Using Global and Regional Numerical Weather Prediction Applications
- Climate Applications of AIRS
- Validation of a 3-Step Cloud Filtering (3-SCF) Method for AIRS Radiances Measured Over the Mediterranean Area
- AIRS Radiance Validation and Constituent Abundance Retrievals
- Determination of Atmospheric Vertical Structure from AIRS

Geoscience Laser Ranging System (GLRS)
Team Leader, Dr. Steven Cohen, GSFC

- Simulation, Determination and Interpretation of Crustal Movements
- Laser Altimetry and Ranging over the West Antarctic Ice Sheet
- Monitoring Crustal Motions in the SW Pacific Region
- Geodetic Studies
- Kinematics of a Diffuse Back-Arc Basin In and Around the Aegean Sea
- Tectonics Motions and Deformations
- Temporal and Spatial Variation of Relative Motion Across the Hayward Fault in the Vicinity of San Francisco: Comparison of GLRS, GPS, and Geodolite
- Relative Plate Motions and Intraplate Deformation of the Anatolian Plate and Surrounding Regions in the Eastern Mediterranean
- GLRS Error Analysis, Instrument Calibration/Verification and Application to Regional and Global Crustal Motions
- Atmospheric Science Investigations by a Modified GLRS Facility Instrument
- Laser Altimetry for Ice Research
- Snow and Ice Altimetry Investigations

High Resolution Imaging Spectrometer (HIRIS)
Team Leader: Dr. Alexander Goetz, University of Colorado

- Application of Atmospherically Corrected Reflectance Spectra from HIRIS to the Identification of Mapping of Aeolian Components in Soils
- High Spatial and Spectral Resolution Remote Sensing of Forest Canopy Chemistry and Nitrogen Cycling
- High Spectral Resolution HIRIS Algorithms for Constituents in Case II Waters
- Advanced Spectral Library Development and Spectral Analysis of HIRIS Data
- Coastal and Open Ocean Phytoplankton Dynamics
- Optical Properties of the Seasonal Snow Cover and Alpine Glaciers in the Earth's Mountain Ranges
- Absolute and Long-Term Calibration of EOS Reflective Imaging Instruments
- HIRIS Processing and Analysis Research
- Applications of HIRIS to the Study and Management of Lakes and Reservoirs
- Relationship of Alkalic-Carbonatite Magmatism with Major Fracture Zones and Plate Motion

Interdisciplinary investigations involve research in more than one of the traditional Earth science disciplines and use data from more than one instrument to provide analysis and conceptual models in preparation, during, and after the data-gathering period of EOS investigations (see Table 2-4).

Interdisciplinary investigations include the outcome of interactions between solar radiation and the ocean; how the global water cycle stimulates and regulates regional and global changes; tracing the patterns and processes of the water, chemical, and nutrient balances of seasonally snow-covered alpine watersheds; interannual variations in climate, biological processes, ocean-atmosphere interactions, and the marine fisheries resources in Australasian waters and fisheries.

TABLE 2-2. Continued

- Detecting Physiological and Structural Properties of Vegetation
- Investigate the Effects of Cloud Inhomogeneities upon Radiative Fluxes and to Supply a Cloud Truth Validation Data Set
- Estimating Ecosystem Biogeochemistry Through Hyperspectral Analysis

Laser Atmospheric Wind Sounder (LAWS)
Team Leader: Dr. Wayman Baker, NOAA

- Study Short-Term Tropical Climate Fluctuations
- Meteorological Analysis and Numerical Weather Prediction
- Sampling Strategies and Wind Computation Algorithms—Storm-Top Divergence Studies
- Development of Techniques for Measurement of Radial Velocities and Studies of Cirrus Cloud Properties, Including Ice/Water Phase from LAWS Returns
- Windfield Structure Studies
- Optimizing the Design of the LAWS System and the Use of Its Data for Numerical Weather Prediction
- Analysis of Atmospheric Effects on the Fidelity of Atmospheric Wind Sounder Velocity Estimates
- On the Use of LAWS Data for Regional Atmospheric Prediction
- Calibration and Archiving of LAWS Data, Aerosol Climatology, and Volcanic Event Planning
- Use of LAWS Data for Tropical Cyclone Prediction

Moderate Resolution Imaging Spectrometer-T/-N (MODIS-T/-N)
Team Leader: Dr. Vincent Salomonson, GSFC

- The Dynamics of Snow and Ice Cover Over Large Areas and Relationships to Surface Radiation Balance Components
- Studies of Primary Production in the World Ocean
- Derivation of Accurate Global Sea Surface Temperature Data Sets
- Infrared Algorithm Development for Ocean Observations
- Algorithms for Ocean Chlorophyll in Case II Waters
- Marine Optical Characterizations
- Oceanic Productivity and Photosynthetic Efficiency
- Processing and Calibration for Visible Ocean Observations
- Species Variability and Improved Carbon and Nitrogen Cycling Determinations
- Determination of Dynamic Vegetation—Soil—Organic Carbon Interactions
- Monitoring Global Vegetation Dynamics
- Investigation of Cloud Properties
- Global Monitoring of Aerosol Properties—Aerosol Climatology, Atmospheric Corrections, Biomass Burning, and Aerosol Effect on Clouds and Radiation
- Determination of Cloud and Aerosol Radiative and Microphysical Properties
- Mapping the Composition and 3-D Structure of Terrestrial Surfaces from a Synergistic Use of EOS Instruments and Numerical Simulation Models
- Ocean Color Algorithm Development and Processing of MODIS-T Data for Australian Waters
- Canopy Carbon and Water Fluxes from Terrestrial Vegetation
- Absolute Radiometric Calibration of MODIS-N and Other EOS Imaging Sensors
- Mapping Spectral Directional Radiance, Spectral Directional Surface Radiance, and Spectral Bidirectional Reflectance; Distribution Functions for Land Surface Covers
- Determination of High Resolution Atmospheric and Surface Parameters
- Global Aerosols Monitoring Experiment from Space (GAMES)
- Estimation of Photosynthetic Capacity using MODIS Polarization
- Land Surface Temperature Measurements

Some of these investigations will entail the development or improvement of quantitative models for assessing the impact of interactions between different Earth system components or for forecasting changes in the global environment. For example, one team will construct and evaluate a simulation model of ecosystem controls over the water, energy, and carbon cycles within grassland areas throughout the world. Another team will develop models to identify volcanic hazards as a precursor to the launch of an operational satellite system that will monitor eruptions.

The interdisciplinary investigation teams are responsible for ensuring that EOS multidisciplinary scientific tasks are adequately performed and will help to guide the development of the EOS Data and

TABLE 2-3. **EOS INSTRUMENT INVESTIGATIONS AND PRINCIPAL INVESTIGATORS**

Investigation Instruments	Scientific Objectives
Clouds and the Earth's Radiant Energy System (CERES): a pair of broadband Earth scanning radiometers similar to the Earth Radiation Budget Experiment (ERBE): Dr. Bruce Barkstrom, NASA Langley Research Center	Long-term measurement of Earth's radiation budget and global measurements of atmospheric Earth radiation from the top of the atmosphere to the Earth surface
Dynamics Limb Sounder (DLS): a 14-channel infrared limb-scanning radiometer: Dr. John Barnett, Oxford University	Measure infrared emission from the stratosphere and mesosphere, and obtain global profiles by day and night
Tropospheric Emission Spectrometer (TES): passive, high-spectral-resolution, cryogenic, infrared, imaging, Fourier transform spectrometer: Dr. Reinhard Beer, JPL, Atmospheric and Oceanograpic Sciences Section.	Determine the horizontal and vertical global distribution of a wide variety of natural and man-made chemical species in the troposphere
Lightning Imaging Sensor (LIS): a staring telescope/filter imaging system: Dr. Hugh Christian, Marshall Space Flight Center	Acquire and investigate the distribution and variability of lightning over the Earth
Multi-Angle Imaging Spectro-Radiometer (MISR): 8 identical CCD-based pushbroom cameras at four viewing angles fore and aft: David J. Diner, JPL Atmospheric and Cometary Sciences Section	Study the effects of geophysical processes and human activities on the Earth's climate
Measurements of Pollution in the Troposphere (MOPITT): a four-channel correlation spectrometer: Dr. James Drummond, University of Toronto Physics Department	Measure carbon monoxide (CO) concentrations in the troposphere to increase knowledge of the lower atmosphere system and how it interacts with the surface, ocean, and biomass
POsitron Electron Magnet Spectrometer (POEMS): a magnet spectrometer with cm^2 Sr collection power: Dr. Paul Evenson, University of Delaware Bartol Research Institute	Particle atmospheric physics and the study of the nature and temporal variation of the charged particle radiation in near-Earth space
Advanced Scatterometer for Studies in Meteorology and Oceanography (SCANSCAT): a dual-scanning scatterometer at 13.995 GHz: Dr. Michael Freilich, JPL Oceanography Group	Obtain accurate, high-resolution all-weather measurements of surface wind speed and direction over the tropical oceans
High Resolution Research Limb Sounder (HIRRLS): 12-channel infrared limb-scanning radiometer: Dr. John Gille, National Center for Atmospheric Research	Sound the upper troposphere, stratosphere, and mesosphere to determine the temperature and concentrations of ozone, methane, water, nitrous oxide, nitrogen oxide, nitric acid, and aerosols
Ionospheric Plasma and Electrodynamics Instrument (IPEI): retarding mass analyzer and ion drift meter: Dr. Roderick Heelis, University of Texas Center for Space Sciences	Measure the ion temperature, composition, and dynamics in the ionosphere
Thermal Infrared Ground Emission Radiometer (TIGER): thermal infrared imaging spectrometer: Dr. Anne Kahle, JPL, Geologic Remote Sensing Group	Surface compositional mapping for geology and volcanology and apply data from comparative global paleoclimate studies and techniques for surface temperature retrieval to agricultural and climatological problems
Geomagnetic Observing System (GOS): boom-mounted vector fluxgate magnetometer; scalar-helium magnetometer: Dr. Robert Langel, III, GSFC Geophysics Branch	Measure the magnetic field of the Earth for studying the Earth's interior and the electrodynamic ionosphere-magnetosphere coupling
Energetic Neutral Atom Camera for EOS (ENACEOS): remote-sensing camera with three sensor heads: Dr. Barry H. Mauk, Applied Physics Laboratory, Johns Hopkins University	Global monitoring of the structure and dynamics of the Earth's magnetosphere, for quantifying magnetosphere/ionosphere/atmosphere coupling
Stratospheric Wind Infrared Limb Sounder (SWIRLS): a gas correlation and filter infrared radiometer that observes atmospheric infrared emissions: Dr. Daniel McCleese, JPL, Earth and Space Sciences Div.	Stratospheric wind measurements to understand the physical mechanisms that determine the structure and dynamics of the stratosphere and the transport of chemically active species like ozone

TABLE 2-3. Continued

Investigation Instruments	Scientific Objectives
Stratospheric Aerosol and Gas Experiment III (SAGE III): an Earth-limb scanning grating spectrometer: Dr. M. Patrick McCormick, NASA Langley Research Center	Measure profiles of aerosols, ozone, nitrogen dioxide, water vapor, and air density between cloud tops and the upper mesosphere. Provides aerosol and cloud data essential for calibrating and interpreting data from other EOS sensors
GPS Geoscience Instrument (GGI): a high-performance Global Positioning System (GPS) flight receiver-processor: Dr. William Melbourne, JPL, Telecommunications Science and Engineering Division	Centimeter-level global geodesy; high-precision atmospheric temperature profiling; ionospheric gravity wave detection and tomographic mapping
X-Ray Imaging Experiment (XIE): X-ray pinhole "anger" cameras with NaI (T1) and PM detectors for >20 keV X-rays proportional gas-filled counter for 3–20 keV X-rays: Dr. George K. Parks, University of Washington, Depts. of Atmospheric Sciences and Physics	To detect and determine the total particulate energy that is precipitated into the Earth's atmosphere
Tropospheric Radiometer for Atmospheric Chemistry and Environmental Research (TRACER): a two-channel gas-filter correlation radiometer: Dr. Harry Reichle, Langley Research Center	To measure the global distribution of carbon monoxide at multiple levels in the troposphere, thereby providing a global database for modeling studies to increase understanding of global NASA tropospheric chemistry and transport processes
Solar Stellar Irradiance Comparison Experiment (SOLSTICE): four-channel UV spectrometer (two-axis solar track): Dr. Gary Rottman, University of Colorado Laboratory for Atmospheric and Space Physics	Provide precise daily measurements of the full disk solar ultraviolet irradiance between 4 to 440 nm with calibration maintained by comparison to bright early-type stars
Spectroscopy of the Atmosphere Using Far Infrared Emission (SAFIRE): a seven-channel far-IR Fourier transform spectrometer (0.004 cm^{-1} spectral resolution): Dr. James M. Russell III, Langley Research Center	Improve knowledge of middle atmosphere ozone distribution through global measurements of the key chemical, radiative, and dynamical processes that influence ozone changes
High-Resolution Microwave Spectrometer Sounder (HIMSS): a high-resolution microwave spectrometer: Dr. Roy W. Spencer, Marshall Space Flight Center	Retrieve numerous atmospheric and oceanic parameters, e.g., precipitation rates over both land and ocean in multiple layers; oceanic cloud water and water vapor content; wind speed and sea surface temperatures; atmospheric temperature profile; snow cover depth and water equivalent
Earth Observing Scanning Polarimeter (EOSP): high-precision, multichannel, scanning photopolarimeter: Dr. Larry D. Travis, NASA Goddard Institute for Space Studies	To determine cloud properties and global distribution of the tropospheric and stratospheric aerosols.
Microwave Limb Sounder (MLS): passive microwave limb-sounding radiometer: Dr. Joe W. Waters, MIT	To study and monitor natural and human influences on the amount of stratospheric and mesospheric ozone
Active Cavity Radiometer Irradiance Monitor (ACRIM): three total irradiance detectors: Richard C. Willson, JPL, Earth and Space Sciences Division	Monitor the variability of total solar irradiance to expand the high-precision database from other ACRIM experiments

TABLE 2-4. **INTERDISCIPLINARY EOS INVESTIGATIONS AND PRINCIPAL INVESTIGATORS**

Investigation	Objectives
Coupled Atmosphere/Ocean Processes Primary Production in the southern ocean: Dr. Mark Abbott, Oregon State University College of Oceanography	To study the circulation, biology, and interaction with the atmosphere of the southern ocean
Global Water Cycle: Extension Across the Earth Sciences: Dr. Eric J. Barron, Earth System Science Center, Penn State University	Investigate the global water cycle to determine the scope of its interactions with all components of the Earth system and to understand how it stimulates and regulates change regionally and globally
The Development and Use of a Four-Dimensional Atmospheric/Ocean/Land Data Assimilation System for EOS: Dr. J. Ray Bates, University of Maryland Department of Meterology	Research on satellite data retrievals, data quality control, objective analysis, initialization, and atmospheric/oceanic/land surface models to optimize EOS data and develop an "Earth System Model"
Long-Term Monitoring of the Amazon Ecosystems through the EOS: From Patterns to Processes: Dr. Getulio T. Batista, Brazilian Institute for Space Research (INPE)	To better understand the processes affecting the Amazonian ecosystems, particularly human influences, and develop a hydrological cycle model of the area's environmental conditions
Biogeochemical Fluxes at the Ocean/Atmosphere Interface: Dr. Peter G. Brewer, Woods Hole Oceanographic Institution	Investigate the influence of solar radiation on the oceans and the feedback of the gaseous products of these interactions through wind, waves, and circulation to the marine atmosphere
Quantifying the Vegetation of Canada: Carbon Budget and Succession Models: Dr. Josef Cihlar, Canada Centre for Remote Sensing (CCRS)	Research, development, and demonstration of a Vegetation Change Information System (VCIS) for routine monitoring of terrestrial vegetation from space
National Center for Atmospheric Research (NCAR) Project to Interface Modeling on Global and Regional Scales with Earth Observing System Observations: Dr. Robert Dickinson, NCAR Climate and Global Dynamics Division	Modeling, data analysis, data systems, and archiving in order to improve global and mesoscale climate models at the National Center for Atmospheric Research
Hydrology, Hydrochemical Modeling and Remote Sensing in Seasonally Snow-Covered Alpine Drainage Basins: Dr. Jeff Dozier, JPL and University of California, Santa Barbara	A detailed understanding of the patterns and processes of the water balance and chemical and nutrient balances of seasonally snow-covered alpine watersheds
Observational and Modeling Studies of Radiative, Chemical and Dynamical Interactions in the Earth's Atmosphere: Dr. William Grose, Langley Research Center, Atmospheric Sciences Division	Increasing our understanding of the radiative, chemical, and dynamical processes which determine the circulation, thermal structure and distribution of constituents of the Earth's atmosphere
Estimation of the Global Water Budget: Dr. Robert James Gurney, GSFC, Hydrological Sciences Branch	Use EOS and other data to estimate global water balances ranging from days to seasons, and to examine their variability over decades with various external forcings
Interannual Variability of the Global Carbon and Energy Cycles: Dr. James E. Hansen, Goddard Institute for Space Studies	Investigate the interannual variability of key global parameters and processes in the global carbon cycle and the global thermal energy cycle. Develop, analyze, and make available data sets derived from pre-EOS and EOS observations in combination with models
Interdisciplinary Studies of the Relationships Between Climate Ocean Circulation, Biological Processes, and Renewable Marine Resources: Dr. Graham Paul Harris, CSIRO Divisions of Fisheries Research and Oceanography, Hobart, Australia	Studying the interannual variability in climate, biological processes, ocean-atmosphere, interactions, and the marine fisheries resources in Australasian waters and fisheries
Climate Processes Over the Oceans: Dr. Dennis L. Hartmann, University of Washington, Dept. of Atmospheric Sciences	Use data from various satellite instruments and from other sources and models to construct an integrated view of the atmospheric climate over the oceans
Tectonic/Climate Dynamics and Crustal Evolution in the Andean Orogen: Dr. Bryan L. Isacks, Cornell University, Dept. of Geological Sciences	Examine the interplay of climate, weathering, mountain building, and rapid plate boundary interaction in the Andean Orogen. Data from various EOS instruments entered into a comprehensive Morphotectonic Information System

TABLE 2-4. Continued

Investigation	Objectives
Hydrologic Cycle—Semi-Arid Areas—Climatological Processes: Dr. Yann H. Kerr, LERTS, Toulouse, France	Derive hydrologic cycle parameters over arid and semi-arid lands. Study soil/vegetation interactions and hydrological feedback mechanisms. Define a global data set and develop models of actual geophysical parameters for monitoring seasonal and yearly changes caused by nature or human activity
The Role of Air-Sea Exchanges and Ocean Circulation in Climate Variability: Dr. W. Timothy Liu, JPL	Examine the variabilities of various terms in the atmospheric energy and water budgets and examine the interaction between different scales of atmospheric processes over oceans
Use of a Cryospheric System (CRYSYS) to Monitor Global Change in Canada: Dr. Lyn McNutt, Canada Centre for Remote Sensing	Delineate specific data collection sites in the Canadian North and identify and access critical data bases as part of a global effort to monitor and evaluate the utility of remote-sensing observations of the cryosphere (the polar regions of the Earth that are frozen) for observing the effects of global changes
Changes in Biogeochemical Cycles: Dr. Berrien Moore, III, University of New Hampshire, Institute for the Study of Earth, Oceans, and Space	Understanding the primary biogeochemical cycles of the planet by studying how element cycles function 1) in quasi-steady-state systems in the absence of human-induced pertubations and 2) in the transient state caused by human activity
A Global Assessment of Active Volcanism, Volcanic Hazards, and Volcanic Inputs to the Atmosphere: Dr. Peter Mouginis-Mark, University of Hawaii	To understand the physical processes associated with volcanic eruptions, to assess the rate of injection and global dispersal of sulfur dioxide into the stratosphere, and to help define and develop methods for identifying volcanic hazards as a precursor to an operational satellite eruption-monitoring system
Investigation of the Atmosphere/Ocean/Land System Related to Climatic Processes: Dr. Masato Murakami, Meteorological Research Institute, Japan	Use spaceborne observational data to 1) develop algorithms for the objective identification of cloud types and quantitative measurement of precipitation; and 2) monitor climatic changes of the sea surface temperature, sea level, and surface winds
Chemical, Dynamical, and Radiative Interactions through the Middle Atmosphere and Thermosphere: Dr. John Adrian Pyle, University of Cambridge, England	Improve understanding of the atmospheric dynamical, chemical, and radiation interactions and thus the ability to predict and detect long-term atmospheric trends in the Earth's climatic and chemical environment
Polar Ocean Surface Fluxes: the Interaction of Oceans, Ice, Atmosphere, and the Marine Biosphere: Dr. Drew Rothrock, University of Washington Applied Physics Laboratory	Observe the surface fluxes and conditions of both the ice-covered and ice-free polar oceans. Several models and algorithms will be developed and combined into a single model of the upper ocean, ice cover, and atmospheric boundary layer
Using Multisensor Data to Model Factors Limiting Carbon Balance in Global Grasslands: Dr. David Schimel, Natural Resources Ecology Laboratory	Develop and evaluate a simulation model of ecosystem controls over the water, energy, and carbon cycles within global grasslands, using data derived from coupling a simple ecosystem model (SEM) with spectral data from several EOS sensors
Investigate the Chemical and Dynamical Changes in the Stratosphere Up To and During the EOS Observing Period: Dr. Mark R. Schoeberl, GSFC Atmospheric Chemistry and Dynamics Branch	Characterize both the short- and long-term stratospheric changes from late 1978 through the EOS observing period to investigate the physics and chemistry of the atmosphere. Distinguish natural from human-induced atmospheric changes
Biosphere-Atmosphere Interactions: Dr. Piers John Sellers, University of Maryland Dept. of Meteorology	Investigate the interaction between land surface and the atmosphere, stressing the biospheric exchanges of energy, water, and carbon to produce new and improved products of derived surface and atmospheric parameters for developing methods to extract maximum benefit from EOS

TABLE 2-4. Continued

Investigation	Objectives
Middle and High Latitudes Oceanic Variability Study (MAHLOVS): Dr. Meric A. Srokosz, British National Space Center	Using the EOS microwave, visible, and infrared sensors to investigate the variability of atmospheric forcing on the North Atlantic and southern oceans, the consequent effect on the oceanic response, and the resulting effect on the oceans' biological productivity
Earth System Dynamics: the Determination and Interpretation of the Global Angular Momentum Budget Using the Earth Observing System: Dr. Byron Tapley, University of Texas, Dept. of Aerospace Engineering and Engineering Mechanics	Develop appropriate system models and use data from multiple EOS sensors and other satellite and in situ sources in order to learn more about the relationship between the atmosphere, oceans, and solid Earth, and the exchange of energy and angular momentum between these Earth system components
An Interdisciplinary Investigation of Clouds and Earth's Radiant Energy System: Analysis (CERES-A): Dr. Bruce Wielicki, Langley Research Center	To provide EOS with a consistent database of accurately known fields of radiation and of cloud properties. This research will further our understanding of the climatic effects of human-induced changes to the Earth's surface

Information System (EOSDIS). These teams will also contribute a strong theory and data analysis perspective toward the planning of the EOS mission.

Planning and Coordination

A variety of working groups, teams, and individuals are responsible for planning and coordinating EOS activities.

The International Coordination Working Group (ICWG) was created in 1986 to coordinate use of Earth observation polar platforms as foreseen at that time by NASA and ESA. The ICWG has expanded to include the Earth observation offices of the other two Space Station partners, Japan and Canada, as well as representatives of the operational organizations in each country: i.e., NOAA (United States), EUMETSAT (Europe), JMA (Japan), and the Canadian Department of the Environment.

In accordance with a charter approved by all participants in 1988, the group meets several times a year to exchange information and to coordinate plans. The ICWG charter allows for expansion to include proposed payloads and platforms agreed on by the group. At present, the group's charter covers the first and subsequent NASA and ESA polar platforms, Space Station attached payloads, the second (and subsequent) NASA and ESA platforms, the first Japanese polar platform, and the proposed NOAA common-interface free flyer series for the afternoon operational payload.

Throughout the duration of EOS, the ICWG will provide programmatic coordination of high-level policy and science consultation and guidance on all science-related long-range mission objectives.

The Investigator Working Group (IWG), which includes the selected instrument and interdisciplinary investigators, along with the facility instrument team leaders, will analyze the scientific data from the EOS-A and EOS-B platforms. IWG members will meet regularly to exchange inter-experiment information, coordinate investigations, and review requests for specific observational sequences and scientific results.

The NASA Calibration Advisory Working Group (CAWG) will set the policies for coordinating all calibration activities. This group is responsible for overseeing the calibration of each spaceborne instrument. Each PI is responsible for developing pre- and in-flight calibration systems, but the host agency will undertake calibration once the instrument is in flight.

The Interagency Working Group on Data Management for Global Change (IWGDMGC). Interagency and international data coordination is already underway. NASA is coordinating data systems planning with a number of other government agencies and international groups. The recently formed Interagency Working Group on Data Management for Global Change (IWGDMGC) is developing an intergovernmental data location and access system for Earth scientists. Group members are NASA, NOAA, the U.S. Geological Survey (USGS), the National Science Foundation (NSF), the U.S. Navy, and the U.S. Departments of Energy and Agriculture (DOE and USDA). The goal of this group is to operate a national data and information system for global change research across agencies, universities, and other user communities by 1995. This system will make it as easy as possible for scientists to access data necessary for studies of global change.

Current Activities

Early in 1989, NASA Headquarters made formal mission assignments to the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, for the planning, design, and development of the EOS-A (NPOP-1) and the EOS-B polar platform (NPOP-2).

The selection of EOS investigations was announced in February and between March 19 and 24 investigators, co-investigators, and team leaders met for the first time at the first EOS IWG meeting, held at Goddard. Short debriefings by NASA Headquarters staff on the selection process were followed by 2 days of 15-minute summaries from each principal investigator, interdisciplinary scientist, and facility instrument team leader, along with briefings from staff of the Goddard Space Flight Center and Jet Propulsion Laboratory Project Offices. A second IWG meeting was held October 11–13, 1989 at the California Institute of Technology, Pasadena, California.

The EOS Non-Advocacy Review (NAR) was held from June 12–16, and on June 15 definition-phase contracts were started to initiate investigations. As already mentioned, as a result of the NAR, the EOS SAR facility instrument has been deferred from the anticipated FY 1991 New Start to a future year budget initiatve.

The EOS Data and Information System (EOSDIS)

The success of EOS depends on the ability to develop a unified, comprehensive data and information system that will give the international Earth science research community affordable, easy, and reliable access in their laboratories to the full complement of data from the space platforms. The system must be able to convert data from the spaceborne instruments rapidly, efficiently, and effectively, into information about the Earth system that is meaningful to the global community of Earth scientists.

The development of this system poses a number of major challenges to NASA:

- EOS studies will generate an enormous amount of data—about 1,000 times more than from previous NASA missions.
- In contrast to previous single disciplinary studies, EOS interdisciplinary and multidisciplinary studies require a data system that can a) integrate information from the many different EOS instruments and b) process the simultaneous measurements by these sensors of different Earth system phenomena, in order to assess the cumulative impact of their interactions. These studies will be coordinated with other federal agencies, universities, and the Earth science community worldwide.
- The development of networks that will enable scientists to exchange information and to interact by computer: a user friendly system is needed to give users prompt access to any bank of Earth science data from a local access point.
- The combination of data from research and operational instrument observations in space with those from ground-based instruments.
- A system with the capability to gather and store past, present, and future data, including comprehensive documentation and quality indicators, so that the results of investigations will be meaningful.
- A capability to integrate and test processing algorithms developed by EOS investigators to generate standard EOS data products.

EOSDIS will incorporate traditional mission data facilities with rapid access to all levels of data (as well as documentation on the processing algorithms and validation of the data) and to data sets and documents resulting from EOS research and analyses. This system will be able to evolve, expand, and adapt to new sources of data and data system technologies. NASA's Communications and Information Systems Division and Office of Aeronautics and Space Technology are developing and testing a variety of new technologies that include experimental computers, optical tape and high-capacity optical/magnetic disk devices for mass data storage, and improved techniques for joint analysis of imagery from multiple sensors.

Consistently calibrated data will be produced so that information collected at the start of the EOS mission will make sense when compared with similar data from the program's 15th year.

EOSDIS will support the EOS flight complement with:

- A flight data system for payload-unique functions

- Facilities for payload flight operations
- A series of processing and distribution elements for science data
- An information and management system for the entire EOSDIS
- Extensive communications networks for the distribution of raw and processed data and information exchange

On the flight segment, EOSDIS will provide payload-unique command processing, data collection, data storage, and control. On the ground, EOSDIS operations will cover the receipt, processing, archiving, management, and distribution of all EOS-generated data including the maintenance of directories, catalogs, inventories, and other information about EOS and ancillary data.

Figure 2-3 shows a diagram of the proposed EOSDIS concept. Since NOAA is providing an operational instrument package for one ESA platform and will be receiving and processing prototype operational data from NASA's polar platforms, NOAA is a major participant in EOSDIS. NASA and NOAA are collaborating on EOSDIS planning so that the research and operations data management systems can be developed and implemented in parallel to facilitate interactions and data sharing between these two systems.

In planning for EOSDIS, the Earth Science and Applications Division (ESAD) is developing an Earth Science and Applications Data System (ESADS). ESADS will integrate successful aspects of existing data systems, the National Space Science Data Center (NSSDC), special Earth science data processing and archiving projects, and flight project data systems, into a distributed Earth science information system. EOSDIS will build on the experience and expertise of these integrated ESADS components. EOSDIS elements will be developed by utilizing prototypes to the maximum extent feasible, with standards established for directories and catalogs, network protocols, archive media and formats, software, user interface and data access, and accounting and billing.

ESAD is also developing WetNet, a prototype Earth science and applications data system to encourage scientists to conduct interdisciplinary studies and to enhance their ability to perform this type of research. A dedicated computerized network will link scientists and engineers, at NASA and universities in the United States and other countries, who are pursuing interdisciplinary studies of the global moisture cycle based on data derived from the space-borne Special Sensor Microwave/Imager (SSM/I) on the Department of Defense Meteorological Satellite. Program planning and participant training have continued with hardware and software scheduled for delivery in January 1990.

International Data Coordination

NASA participates in a number of international data-sharing and data management and coordination enterprises that provide valuable experience for EOSDIS. One of these is an experimental data-sharing system sponsored by the United Nations, known as the Global Resources Information Database (GRID), which links the United States, Europe, and Africa. NASA is also working with the Committee on Earth Observation Satellites (CEOS) to coordinate data and information systems.

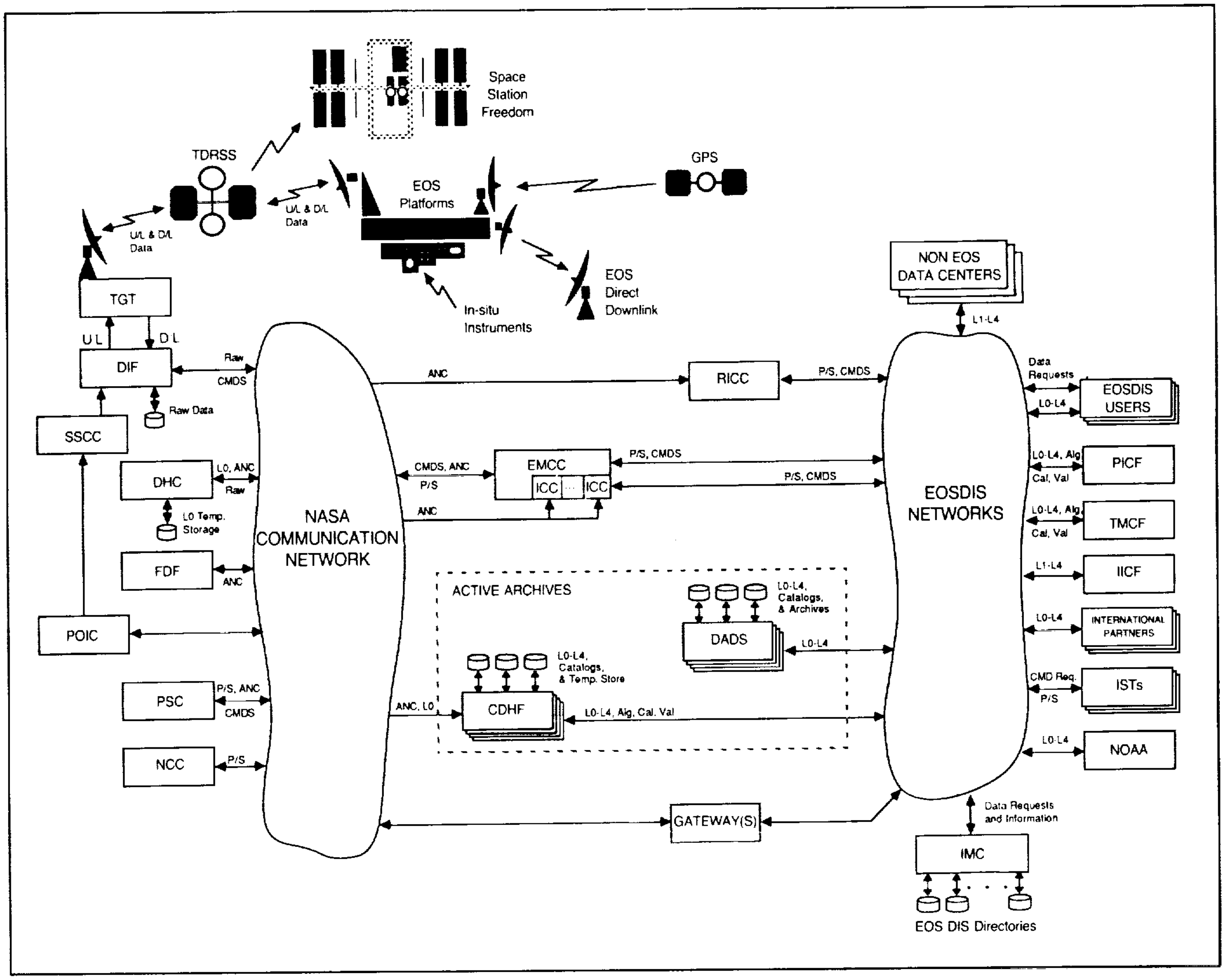
Another excellent learning opportunity will be provided by the 1992 International Space Year (ISY) program, in which space officials from 23 nations will collect data from more than 20 Earth-viewing satellites to be launched over the next 6 years. This international effort will help to pave the way for the more complex international coordination needed for EOSDIS.

Functional Responsibilities

The EOS-unique elements are shown in Table 2-5. EOSDIS covers three areas of functional responsibility: Mission Operations, Instrument Operations, and Data Operations.

- The EOS Mission Operations Center at Goddard Space Flight Center (EMOC) will coordinate the operation of EOS instruments on the U.S. platforms and provide the primary point of contact between the EOS mission and the Space Station Information System (SSIS) for mission operations. This Center will monitor EOS operations by processing and displaying instrument status information received from the Instrument Control Centers and ancillary data from the Data Handling Center.
- The Instrument Control Centers (ICC) will handle instrument operations, including the equipment and personnel necessary to plan, schedule, command, and operate the instrument. The ICCs will develop a detailed instrument plan based on the IWG science plan, platform resource allocations, orbit data, and other

FIGURE 2-3. **EOSDIS CONCEPT**



Alg - Algorithms
ANC - Ancillary Data
Cal - Calibration Data
CDHF - Central Data Handling Facilities
CMDS - Commands
DADS - Data Archive & Distribution System
DHC - Data Handling System
DIF - Data Interface Facility
D/L - Downlink
EMOC - EOS Mission Operations Center
FDF - Flight Dynamics Facility
ICC - Instrument Control Centers
IICF - Interdisciplinary Investigator Computing Facilities
IST - Instrument Support Terminal
L - Data Level
NCC - Network Control Center
NOAA - National Oceanic & Atmospheric Administration
P - Planning
PICF - Prinicipal Investigator Computing Facilities
POIC - Payload Operations Integration Center
PSC - Platform Support Center
Raw - Raw Data
RICC - Remote Instrument Control Center
S - Scheduling
SSCC - Space Station Control Center
TGT - TDRSS Ground Terminal
TMCF - Team Member Computing Facilities
U/L - Uplink
Val - Validation Data

guidelines from the EOS Mission Operations Center.

- Data operations will be performed by the Active Archives, Principal Investigator Computing Facilities, Team Member Computing Facilities, and Interdisciplinary Investigator Computing Facilities. This involves the production, short-term storage, and dissemination of scientifically useful data sets from EOS data.

TABLE 2-5. **EOSDIS ELEMENTS AND FUNCTIONS**

Element	Functions
EOS Mission Operations Center (EMOC)	Payload planning and scheduling
Instrument Control Centers (ICCs)	Command generation and monitoring of specific platform instruments
Instrument Support Terminals (ISTs)	Link principal investigators (PIs) or team leaders to ICCs
Active Archives	Process, distribute, and archive data from instruments and principal investigators
Information Management Center (IMC)	Centralized data information management for EOSDIS
Principal Investigator Computing Facilities (PICFs)	Develop and maintain algorithms and validate data at PI locations
Team Member Computing Facilities (TMCFs)	Develop and maintain algorithms and validate data at team member locations
Interdisciplinary Investigator Computing Facilities (IICFs)	Conduct studies and produce higher-level data sets at interdisciplinary investigator locations
Onboard Payload Executive	Flight segment functions: EOS payload commanding; data acquisition, processing; rescheduling; and fault management
Onboard Tape Recorder Storage	Flight segment element providing storage for selected EOS science and engineering data
Onboard Data Processing	Flight segment element providing selected science data processing

Current Status

The Phase A study of the EOSDIS conceptual design was completed when the architecture was approved in late 1986. All Pre-Phase B studies culminated in the July 1988 EOSDIS Baseline report. Using this baseline design as a starting point, Phase B studies are now being conducted by Hughes and TRW, which won contracts in January 1989 for concurrent 15-month studies. During this 15-month period and beyond, a team of EOS investigators and other scientists will provide scientific guidance for the development of EOSDIS.

A joint U.S. Geological Survey/NASA definition and implementation plan is being developed as a follow-on to the USGS/NASA Memorandum of Understanding (MOU) signed in March 1988. This plan includes:

- Establishing active short- and long-term archives to include processing and distribution at the USGS EROS Data Center in Sioux Falls, South Dakota
- Involving USGS in EOSDIS planning, development, and implementation

A similar NOAA/NASA definition and implementation plan is being developed as a follow-on to the NOAA/NASA MOU signed in August 1989.

In 1991, a contractor will be selected to finalize the design, to build, and to test EOSDIS. It is anticipated that one year of system testing, including algorithm integration and training, will be necessary before the launch of the first polar platform in 1997.

3

Studies of Stratospheric Ozone

Since the British Antarctic Survey reported a large, relatively sudden, and unanticipated decrease in the abundance of Antarctic ozone each spring since 1979, the issue of the ozone hole has become a major focus of Earth science investigation.

The International Ozone Trends Panel, formed in 1986 under the auspices of NASA, the National Oceanic and Atmospheric Administration (NOAA), Federal Aviation Administration (FAA), World Meteorological Organization (WMO), and the United Nations Environmental Program (UNEP), undertook a re-evaluation of almost all ground-based and satellite data for total column and vertical profiles for ozone. The panel report, published in March 1988, confirmed the large and sudden loss of ozone over Antarctica in the austral springtime. The report also indicated decreases in ozone of varying degrees across the Northern Hemisphere.

In the fall of 1987, NASA organized a major airborne expedition to Antarctica to study this phenomenon. Co-sponsors were NOAA, the National Science Foundation (NSF), and the Chemical Manufacturers Association (CMA). The Antarctic campaign demonstrated that substantial ozone losses occurred during the month of September. Data from instruments aboard NASA's ER-2 and DC-8 aircraft that flew south from Punta Arenas, Chile, and from ground-based observations at McMurdo Station in 1986 and 1987, directly implicated man-made chlorofluorocarbons in the ozone loss over this remote region in the Southern Hemisphere. Atmospheric chemicals containing chlorine and bromine efficiently destroy ozone in the Antarctic lower stratosphere during the austral spring because of its special meteorological conditions:

- A very cold air mass is largely protected against exchange with mid-latitude air by the dynamical effects of a band of strong circumpolar winds (polar vortex).
- The cold temperatures found inside the vortex permit the formation of Polar Stratospheric Clouds (PSCs) which significantly perturb the chemical composition of the lower stratosphere by allowing heterogeneous chemical reactions on the PSC surfaces to occur.
- Sunlight drives the chlorine monoxide radical (ClO) and bromine monoxide radical (BrO) ozone-destroying cycles while the vortex is still intact.

In this region, the substantial ozone losses were broadly consistent with the observed levels of ClO and the exposure to sunlight.

These results increased speculation among scientists that a similar phenomenon might be occurring in the Arctic, although the winter temperature is warmer than in the Antarctic. Recent observations of a few key chlorine (chlorine monoxide radical and chlorine dioxide) and nitrogen (nitrogen dioxide) species in the Arctic winter stratosphere had given preliminary indications of perturbed chemistry.

The 1989 Arctic Expedition

The 1989 Airborne Arctic Stratospheric Expedition is one of the most recent scientific studies of the Earth's atmosphere to address the serious problem of global ozone depletion. This expedition was jointly undertaken by NASA and NOAA as a follow-up to the 1987 study of ozone in the Antarctic. Again, co-sponsors were NSF and CMA.

The expedition was scheduled for early winter, statistically the best time to study the influence of PSC-induced heterogeneous chemistry. In addition, the International Ozone Trends Panel had found that the largest decreases in total ozone occurred during January and February at latitudes near the edge of the Arctic vortex. Figure 3-1 shows TOMS data from the end of January 1989, which indicates an area of decreased ozone levels over Norway as compared with higher ozone levels over the rest of Europe, the Soviet Union, and the Atlantic.

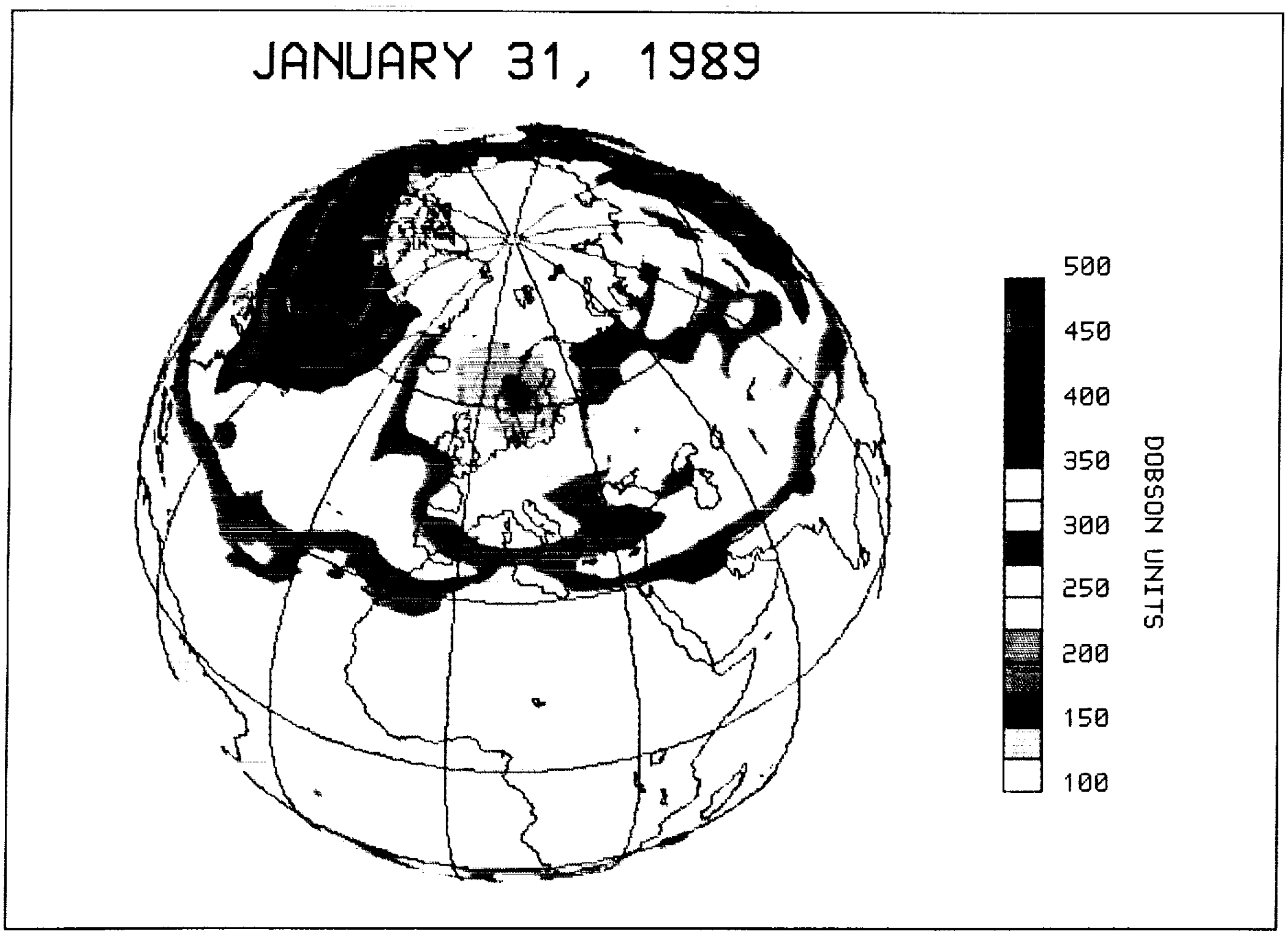
In addition to establishing whether the processes that contribute to the Antarctic ozone depletion also operate in the Northern Hemisphere, the mission sought to:

- Observe and understand the atmospheric conditions that lead to the formation of PSCs (polar stratospheric clouds)
- Obtain evidence of perturbed chemistry (i.e., different from that incorporated in the current global stratospheric models which do not include the influence of PSCs)
- Verify that PSCs do play a role in perturbing the chemical composition of the Arctic stratosphere
- Observe and understand the impact of chemically perturbed Arctic air on ozone and identify the role of atmospheric transport in modulating the effects of chemistry

On February 17, 1989, two days after completion of the Arctic mission, the participating scientists released their key *preliminary* findings in order to keep the public and policymakers up-to-date on the problem of global ozone depletion due to human activities.

These findings indicated that the chemical composition of the Arctic winter polar stratosphere was highly perturbed and that these perturbations occur over a wide range of altitudes. Levels of chlorine

FIGURE 3-1. **ARCTIC STRATOSPHERIC EXPEDITION**



Data from TOMS on Nimbus-7 show an area of depressed ozone levels (150-200 Dobson units) over Norway. It is surrounded by much higher levels over Europe (250) and the Atlantic and the U.S.S.R. (over 300).

monoxide and chlorine dioxide were much higher than expected and levels of hydrochloric acid, nitric oxide, and nitrogen dioxide were lower than anticipated. As in the Antarctic, such chemical perturbations are the result of chemical reactions occurring on the PSCs. In the Antarctic, significant ozone loss occurs as a result of such PSC-induced, chlorine catalyzed processes. However, there is no ozone hole in the Arctic as there is in the Antarctic. The Antarctic circulation is driven more radiatively than in the Arctic, resulting in much colder stratospheric temperatures, more PSCs, and a much stronger west to east jet stream than in the north. In the Arctic, the vortex usually breaks up, temperatures rise, and mid-latitude air is mixed in before the return of sunlight to the pole. The expedition's preliminary findings indicated:

- The chemical composition of the Arctic polar stratosphere was highly perturbed.

- In comparison with models that exclude chemical reactions occurring on the surfaces of PSCs:

  - the observed amount of the ozone-depleting chlorine monoxide radical (ClO) was higher by up to a factor of 50 in the Arctic lower stratosphere
  - the abundance of chlorine dioxide (OClO) was up a factor of 50, consistent with increased amounts of ClO in the presence of bromine monoxide radicals (BrO)
  - the abundance of the major inactive chlorine reservoir, hydrochloric acid (HCl), was considerably reduced, indicating that there had been a conversion from the inactive to the active (ozone-depleting) chemical forms of chlorine
  - the abundances of nitric oxide (NO) and nitrogen dioxide (NO_2) were significantly reduced, thereby preventing the reconversion of ClO into an inactive form of chlorine.

- The measurements of the column abundances of several of the above compounds indicate that these perturbations occur over a wide range of altitudes in the stratosphere.

- All of the above observations add up to a consistent conclusion similar to the one derived from the Antarctic data in 1987, namely that strong perturbations in stratospheric chemical composition are due to chemical reactions occurring on the PSCs that form at extremely cold temperatures.

- The chemical changes were associated with the presence of PSCs and are consistent with their role in (a) shifting the partitioning between the active and inactive chlorine compounds, (b) removing the nitrogen oxides (NO + NO_2), and (c) removing and repartitioning NO_y (the sum of all nitrogen-containing reservoir and radical species).

- No unequivocal signature of photochemical loss of Arctic ozone was identified before completion of this mission. However, by the end of the mission, a considerable portion of the vortex air was primed for ozone destruction.

- It is difficult to predict the degree of Arctic ozone depletion that will actually occur, because it depends on the rate at which normal partitioning of chlorine species is reestablished. This rate is uncertain because:

  - the level of exposure to sunlight is uncertain
  - the degree of denitrification of the Arctic stratosphere (indicated by the amount of nitric acid (HNO_3) has not been adequately quantified with respect to altitude
  - the rate at which the Arctic air mixes with air containing ambient levels of the oxides of nitrogen is difficult to predict reliably.

- The relevant meteorological conditions for the formation of PSCs in the Arctic polar region were not unusual this year. Hence, the phenomena observed are expected to occur in most years.

- Until a comprehensive analysis of the data from this mission is accomplished and model calculations are performed, it is not clear whether the high latitude winter ozone decreases reported by the International Ozone Trends Panel are due to the perturbed Arctic chemistry.

- The observed PSC-induced buildup of reactive chlorine compounds represents an additional ozone-depleting process that was not included in the stratospheric ozone assessment models used as a basis for the Montreal Protocol on Substances that Deplete the Ozone Layer, which went into effect on January 1, 1989.

The preliminary results of this mission have substantially increased confidence in the scientific understanding of the PSC-induced, chlorine catalyzed, ozone depletion phenomenon. As a result, it is clear that enhancements of chemically active chlorine compounds do indeed occur in both the Arctic and Antarctic stratosphere.

The expedition took place between January 1 and February 15, 1989. During this period, two NASA aircraft, an ER-2 and DC-8 made 14 flights each from Sola Airfield near Stavanger, Norway. DC-8 flights reached the North Pole and the west coast of Greenland, while the ER-2 flew as far as 82°N and to central Greenland. These aircraft were equipped with the same instruments for measuring the chemical composition and physical state of the atmosphere as those used for the Airborne Antarctic Ozone Experiment. Satellite and ground-based measurements complemented those made from the aircraft and teams of theorists participated with the experimentalists in flight planning and analysis of the data collected. In addition, the mission was aided by normal weather forecasts and forecasts of air parcel trajectories and potential vorticity maps, which can be used to trace the movement of air masses of interest, and to define the vortex dynamics.

Major contributions to the campaign were made by the United Kingdom Meteorological Office and Department of the Environment, and the Norwegian Department of the Environment and Meteorological Institute. Scientists, engineers, and other personnel who participated in this campaign include those from the Universities of Denver and Harvard, Pennsylvania State University, Cambridge University (UK), the University of Oslo, (Norway), Kernforschungsanlage (KFA) in Julich (Federal Republic of Germany), the National Center for Atmospheric Research and Jet Propulsion Laboratory. The Norwegian government hosted the airborne campaign and the Royal Norwegian Air Force supplied the facilities and logistical support.

Two full science team data workshops were scheduled five and eleven months after the Arctic expedition. After the first science team meeting, participating investigators were encouraged to submit papers for publication. At this time, the experimental and theoretical teams directly associated with the project could bring in outside investigators to help analyze their data.

The initial release of the scientific data from the Arctic mission was planned for approximately 12 months after its completion, February 1990. It is expected that almost all of the data, including results from theoretical models and weather data, will be reduced and recalibrated if necessary, and that these data will be available immediately for distribution in the form of a CD-ROM, as was done for the Antarctic campaign.

It is anticipated that major scientific conclusions and supporting data will be released at this time to the scientific community at a workshop or meeting, or through articles published in a special journal issue. By February 1990, the scientific community will have access to all *reduced* data from the Arctic mission.

The United Nations Environment Program Panel Reports

Article 6 of the Montreal Protocol on Substances that Deplete the Ozone Layer requires that its international ozone control measures be reviewed in 1990, and every 4 years thereafter, on the basis of currently available scientific, environmental, technical, and economic information. To meet this requirement, a United Nations Environment Program (UNEP) Ad Hoc Working Group which was meeting at The Hague in October 1988, established four panels of experts and outlined their terms of reference and timetables for completing reviews of available scientific, environmental, technical, and economic information.

An integrated report of the major findings of these four panels was presented for review to a Working Group meeting in Nairobi, Kenya August 28–September 5, 1989. The final report will provide key input for any proposed amendments to the Montreal Protocol.

The Ozone Scientific Assessment Panel, chaired by two U.S. scientists and consisting of 136 scientists from 25 countries, reported significant advances in the understanding of how human activities affect the Earth's protective ozone layer. In its preliminary report, this panel cited four major findings since the signing of the Montreal Protocol, which have increased concern that chlorine- and bromine-containing chemicals can lead to a substantial loss of stratospheric ozone:

- Scientific evidence strongly indicates that chlorinated (largely man-made), and brominated chemicals are primarily responsible for the recently detected large decreases of stratospheric ozone over Antarctica in springtime.

- Despite the current lack of measurable ozone depletion over the Arctic comparable to that over the Antarctic at present, the same potentially ozone-destroying processes have been identified in the Arctic stratosphere.

- Analyses of the total-column ozone data from ground-based Dobson instruments show long-term, measurable downward trends from 1969 to 1988 of 3 to 5 percent (i.e., 1.8–2.7 percent per decade) in the Northern Hemisphere (30 to 64°N latitudes) during winter that cannot be attributed to known natural processes.
- The recognition of major gaps in theoretical models currently used for assessment studies. These models do not provide adequate simulations of PSC chemistry or polar meteorology.

The identified major public policy implications of ozone research over the past few years include the following:

- The 1987 Montreal Protocol was based on the prediction that substantial ozone layer depletion would eventually occur, yet the Antarctic ozone studies show that this phenomenon has already occurred.
- The observed PSC-induced buildup of reactive chlorine compounds over the Arctic and Antarctic represents an additional ozone-depleting process that was not included in the stratospheric ozone assessment models used as the basis for the Montreal Protocol.
- Future global ozone layer depletions may well be greater than originally predicted because recent laboratory studies suggest that similar reactions involving chlorine compounds may occur on sulfate particles existing at lower latitudes. This could be particularly important immediately after a volcanic eruption.
- Even if every nation implemented the Montreal Protocol control measures, today's atmospheric abundance of chlorine (about 3 parts per billion by volume [ppbv]) would double or triple during the next century.
- A complete phaseout of all fully halogenated chlorofluorocarbons (HCFCs), halons, carbon tetrachloride, and methyl chloroform, as well as careful consideration of the HCFC substitutes will be necessary in order to restore the Antarctic ozone layer to levels approaching its natural state and to prevent the possible ozone dilution effect of the Antarctic ozone hole at other latitudes.

Preliminary conclusions are that the prediction that total chlorine and bromine loadings of the atmosphere will approximately triple by the year 2050 and lead to total column ozone depletions of 0 to 3.5 percent in the tropics and 3.5 to 11 percent at high latitudes. Antarctic ozone loss would be comparable or worse than at present, and substantial Arctic ozone depletion would be more likely to occur. The Antarctic ozone hole would not disappear until the atmospheric abundance of chlorine was reduced to 1.5–2 ppbv, the levels of the early 1970s, while the atmospheric abundance of bromine should be reduced below its current level.

The four panels pointed out that atmospheric chlorine and bromine could be stabilized at today's levels through a phase-out of CFCs, carbon tetrachloride, methyl chloroform, and the halons. However, it will take the atmosphere many decades to centuries to fully recover from such chemicals as CFCs, which have long atmospheric lifetimes. Hence 100 percent compliance by all nations in ceasing their production and emission of the ozone-depleting chemicals is of vital importance for protecting the ozone layer. It was concluded that a virtual phase-out of the five controlled CFCs, of methyl chloroform production and use, and of carbon tetrachloride emissions by the year 2000 was technically feasible, since substitutes presently exist for virtually all of their uses. This phase-out would require worldwide commercial availability of the substitutes that are now available or being developed.

The review panels also concluded that ozone depletion is a global problem because of its potential harm to people in all parts of the world. They suggested that protection of the ozone layer would require a full partnership between the developed countries that produced the chemicals causing ozone depletion and the developing countries who would like to use the very same chemicals in order to raise their standard of living.

Ground-Based Lidar Systems

Clearly, long-term, precise measurements of stratospheric ozone concentrations are of the utmost importance because of concern over ozone's response to injections of anthropogenic gases. There is continuing concern that the total column and vertical distribution of ozone is being affected by changing concentrations of atmospheric chemicals including CFCs, carbon dioxide, nitrogen oxide, and methane.

However, data from satellite instruments measuring ozone are not always accurate because these instruments are subject to sensitivity changes during operation in space and current technology does not permit in-flight recalibration.

There are also problems with the Umkehr ozone measuring technique. This technique has been used to obtain the longest database available for altitude-resolved measurements through vertical ozone profiles up to about 48 km with a resolution of about 5 km. The Umkehr method is vulnerable to errors because the indirect inversion method it requires has limited vertical resolution and because of the non-uniqueness of its ozone profiles. Factors such as instrument adjustment and calibration, nonrepresentativeness of first-guess ozone profiles, temperature dependence of ozone absorption coefficients, and aerosol optical effects all introduce errors. Aerosols in particular, are found to have a major bearing on the quality of the data. For example, the volcanic eruption of El Chichon in April 1982 injected large quantities of dust into the stratosphere, rendering the Umkehr record unusable for this period. The Ozone Trends Panel has concluded that the Umkehr technique cannot be used as a primary tool for continuous monitoring of the vertical ozone distribution.

The SAGE I and II (Stratospheric Aerosol and Gas Experiment) spaceborne spectrometers also measure the vertical distribution of ozone. Results from these two instruments appear to be the least sensitive to changes in performance over time in space. The Ozone Trends Panel's reanalysis of the SAGE data indicates a change in the ozone near 40 km of between +1 percent and −7 percent.

The minimum in the 11-year solar sunspot cycle was passed in 1986 and it is predicted that the total column of ozone should rise between 1986–1991. In the Northern Hemisphere, the ground-based Dobson Network is probably adequate to monitor these changes, which may offset the decrease in column ozone induced by the increasing abundance of various atmospheric trace gases, in particular chlorofluorocarbons. However, the atmospheric chemistry models continue to predict a non-uniform decrease in ozone concentration as a function of altitude with the maximum effects still expected to occur near 40 km. Thus it is of prime importance to monitor the ozone concentration profile up to at least 45 km altitude with instruments capable of the precision and range resolution and with the temporal continuity to allow statistical trend analyses.

Global coverage obtained by satellites is preferable to the limited geographic coverage provided by such ground-based networks as the Dobson Network and the proposed Network for the Detection of Stratospheric Change (NDSC) supported by NASA, NOAA, and the CMA. Yet the limitations of satellite data suggest that the application of satellite instruments for sensitive trend detection during the next decade must be questioned. For this period, ground-based stations will provide not only normalizations for the space instruments but also sufficiently precise data for the detection of trends in the local ozone column or profile.

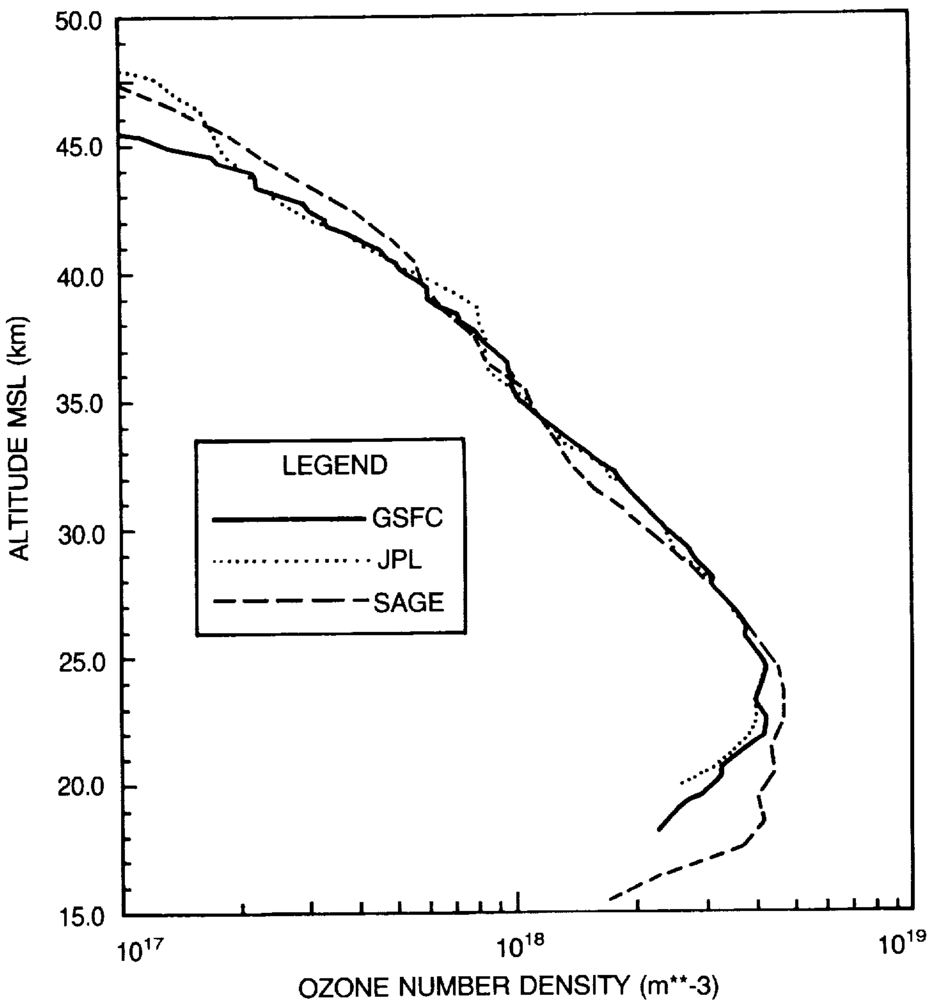
Planning for the implementation of a network of ground-based instruments for long-term measurements has been in progress since March 1986. This network of instruments would provide the earliest possible detection of changes in the composition and structure of the stratosphere, and more importantly, the means to understand the causes of those changes. It would make measurements of a number of species and parameters including, but not limited to:

- Total ozone column
- Vertical profiles of ozone, temperature, chlorine monoxide radical, water vapor, and aerosols
- Stratospheric column content of nitrogen dioxide, hydrochloric acid, methane, nitrous oxide, nitric acid, and chlorine nitrate

A ground-based measurement station can make frequent observations, if the weather permits, and thus accumulate long-term databases essential for trend detection. In addition to meeting the long-term objectives of early detection and understanding of stratospheric changes, the network of ground-based instruments could provide ground-truth and complementary measurements for such space-based systems as NASA's Upper Atmosphere Research Satellite (UARS) and EOS in the 1990s, and provide information on the temporal and spatial variability of the stratosphere.

During the last 10 years, the capability of lidar systems to make range resolved measurements of atmospheric ozone has been demonstrated in Europe, Japan, and more recently in the United States. In France, an ozone lidar system has been in use at the Observatoire de Haute Provence (OHP) since 1981. The system has undergone many improvements since then and has been used for routine measurements since October 1986. An excimer lidar system was making stratospheric ozone measurements at Zugspitze in the German Alps. Much of the early work in applying the xenon chloride excimer laser to atmospheric ozone measurements was carried out in Japan by the group at Kyushu University.

FIGURE 3-2. **OZONE INTERCOMPARISON AT JPL'S TABLE MOUNTAIN OBSERVATORY - NOVEMBER 8–9, 1988**



The Jet Propulsion Laboratory Table Mountain Observatory (TMO) Excimer Laser DIAL System for Stratospheric Ozone Measurements, is a ground-based differential absorption lidar system. In January 1988 this system began to make long-term, precise measurements of stratospheric ozone concentration profiles from 20 km to 50 km altitude. Situated at an elevation of 2,300 meters in the San Gabriel Mountains northeast of Los Angeles, the lidar system uses a high power (100 W) excimer laser system and a 90 cm diameter telescope. Since beginning operations in January 1988, the TMO Lidar has measured ozone profiles on 103 different nights and made measurements every month.

A mobile, trailer-mounted, differential absorption lidar, capable of making precise and accurate measurements in the stratosphere between 20 and 45 km, has been developed at NASA's Goddard Space Flight Center (GSFC). The GSFC instrument was deployed at the TMO from mid-October to mid-November 1988 for the purpose of intercomparing with the JPL lidar, rocket ozonesondes (ROCOZ), and the SAGE II satellite.

Preliminary comparison of the JPL TMO profiles with those of the SAGE II spaceborne spectrometer measured in March and October show good agreement, as do comparisons with the findings of the GSFC ozone lidar system and balloon ozonesondes made during the fall intercomparison campaign, (see Figure 3-2). The TMO Lidar is capable of making routine measurements of stratospheric ozone profiles and will continue operating in order to develop a substantial database suitable for sensitive trend direction and early warning of stratospheric changes.

In July and August of 1989, the NASA Upper Atmosphere Research Program organized a Stratospheric Ozone Intercomparison Campaign (STOIC) at the TMO, in which the JPL and the GSFC lidars and a microwave radiometer from the Millitech Laboratory took part. The Millitech microwave radiometer is a millimeter wave spectrometer, which measures stratospheric ozone by observing the naturally occurring spectral line emission produced by thermally excited ozone directly. It is most sensitive for detecting ozone at altitudes between 23 and 67 km. To assess the performance of these new instruments, the validation/intercomparison campaign used established techniques: balloon ozonesondes launched from Wallops Flight Facility (WFF) and from NOAA GMCC (Geophysical Monitoring for Climate Change), a NOAA GMCC Dobson, and a Brewer from the Atmospheric Environment Service of Canada, both being used for column as well as Umkehr profile retrievals. Column ozone data were also obtained with the Atmospheric Trace Molecule Spectroscopy (ATMOS) infrared instrument. All these instruments were located at the TMO, and measurements were made as close together in time as possible to minimize atmospheric variability. Daytime rocket measurements of ozone were made by WFF personnel using ROCOZ-A instruments launched from San Nicholas Island. The entire campaign was conducted as a blind intercomparison, and investigators did not see each other's data until all data had been archived. Satellite data were obtained from SAGE II and TOMS on Nimbus-7, and the SBUV/2 on NOAA's TIROS.

A preliminary examination of the data has found excellent agreement among the techniques, especially in the 20–40 km range. It is clear that instruments such as the JPL TMO Excimer Laser DIAL System and the NASA Goddard Stratospheric Ozone Lidar Trailer Experiment will contribute significantly to our understanding of the extent of global ozone depletion. The data produced by this ground-based system will complement the findings of the various satellite instruments to provide scientists with a more comprehensive understanding of ozone in the Earth's atmosphere.

4

U.S.–U.S.S.R. Collaboration in Earth Science

Since 1987, the United States and the Soviet Union have been formally collaborating in space science research under the auspices of the Agreement Concerning Cooperation in the Exploration and Uses of Outer Space for Peaceful Purposes, which was signed on April 15 of that year. It was agreed that both parties would cooperate in space science research in the five areas of solar system exploration, space astronomy and astrophysics, Earth sciences, solar-terrestrial physics, and space biology and medicine.

Joint working groups have been formed to carry out research in these five fields. These groups are cooperating on 16 projects, including the following:

- Coordination of activities in the study of global changes of the natural environment
- Coordination in the Cosmos biosatellite program
- Coordination of observations from solar terrestrial physics missions and the subsequent exchange of appropriate scientific data
- Exchange of appropriate biomedical data from U.S. and U.S.S.R. manned space flights

The Earth sciences group is working in global biosphere dynamics; trace gases; global water and energy cycles; geology; and ocean remote sensing.

The recommendations of these joint working groups are subject to the approval of each nation in accordance with its appropriate national procedures. The designated cooperation agencies notify one another of any action taken by the two nations on these recommendations within 3 months of their adoption by the joint working groups.

Both nations have agreed to cooperate through mutual exchanges of scientific information and delegations, meetings of scientists and specialists, and other ways as mutually agreed, including exchanges of scientific equipment where appropriate. This cooperation was expanded on May 31, 1988, when both nations agreed to an amendment to the original Agreement. This amendment has added the two following items to the previous list of 16 cooperative projects:

- Exchange of flight opportunities for scientific instruments on each other's spacecraft
- Exchange of the results of independent national studies being conducted by the two countries on future unmanned solar system exploration missions in order to assess the prospects for U.S./Soviet cooperation on such missions

This amendment paved the way for the proposed flight of a Total Ozone Mapping Spectrometer (TOMS) on a Soviet Meteor-3 satellite, planned for launch in the fall of 1991.

Total Ozone Mapping Spectrometer (TOMS)

American and Soviet space officials have agreed to this mission in order to study ozone depletion in the Earth's atmosphere. The goal of this cooperative program is to continue the mapping of global ozone from space in order to study evidence of global and regional ozone depletion, such as changes in the Antarctic ozone hole. This joint project strongly supports the Vienna Convention on International Protection of the Ozone Layer.

The TOMS is a second-generation backscatter ultraviolet ozone sounder. This instrument measures total ozone by observing both incident solar irradiance and backscattered ultraviolet radiation at six wavelengths between 300–380 nanometers (nm). In operation since 1978 aboard Nimbus-7, TOMS has provided reliable high-resolution mapping of global total ozone on a daily basis for over 10 years. It was data from the TOMS that confirmed the British Antarctic Survey's finding of the large Antarctic ozone hole. TOMS observations showed that the ozone loss occurred throughout the polar vortex and traced the development of the hole after sunlight reaches the polar vortex in late August.

The longevity of the TOMS has proven invaluable for the long-term observations needed to determine the extent to which changes in global ozone are due to human activities (e.g., production of chlorofluorocarbons, burning of fossil fuels) as opposed to natural causes. This instrument has also measured sulfur dioxide (SO_2) emissions from volcanic eruptions throughout the world.

The flying of another TOMS on a Soviet Meteor-3 satellite would meet the long-term requirement for comprehensive daily total column ozone measurements. This new TOMS is designed to create almost global daily maps by taking about 200,000 measurements of all sunlit areas every day. Observational data from this instrument would be downlinked to receiving stations in both the United States and the U.S.S.R.

Thus far, three meetings have been held between American and Soviet specialists since October 1988: two in Moscow and the last one at the NASA/Goddard Space Flight Center in October 1989. At these meetings, the two sides formed joint working groups which met for in-depth discussions on electrical interface, mechanical/thermal interface, data reduction and analysis, launch schedule, science, mission operations, and test and integration. To date, studies have confirmed that the Meteor-3 spacecraft and the TOMS instrument are compatible.

Three major topics were addressed at these meetings: the launch schedule; data reduction and analysis; and data validation and comparison of results.

Launching of the Meteor-3 spacecraft carrying the TOMS is planned for the fall of 1991. The spacecraft will fly in a circular, near-polar orbit at an altitude of approximately 1,200 km and 82.5 degree inclination. Both sides agreed on the following scientific priorities for this mission:

- Maximum coverage of ozone at Antarctic latitudes during the months of September and October

- Maximum coverage of ozone at Arctic latitudes during the month of February, augmented with coverage during January and March

- Coverage of ozone during related field experiments to be conducted by the U.S.S.R. and the United States.

NASA will provide flight and ground support hardware, documentation, and services while the U.S.S.R. will provide facilities, flight hardware, documentation, launch services, mission operations, pertinent spacecraft housekeeping data, and data collection needed for implementation of this project.

It was agreed that algorithm information would be exchanged and data reduction and analysis procedures structured in order to meet the requirement for real-time data (6–9 hours after acquisition). It was also agreed that U.S. and Soviet computer codes should be similar and that both processing (receiving) centers would use compatible equipment.

Discussions continued on the data validation plan, particularly algorithm accuracy. The maintenance of the long-term instrument calibration of TOMS will be validated by comparison of its measurements of the total ozone column with those from other instruments. The three major systems that also measure the total column of ozone on a regular long-term basis at present are the ground-based stations of the Dobson network operating throughout the Northern Hemisphere, and those of the Soviet M124 and Brewer networks. Aboard the Nimbus-7, TOMS measurements have been compared with those of the stations in the Dobson network. TOMS measurements can also be compared with those of DIAL LIDAR and the Soviet SUVS instrument. Ozone profile measurements will serve to verify the accuracy of the algorithms, and ground-based measurements from rocket, balloon, and airborne instruments will be used for this purpose. Additional data will be obtained from other American and Soviet satellite instruments. After independently computing total ozone from the TOMS radiances, Soviet and American investigators will exchange archival data tapes in a common format in a timely manner in order to facilitate rapid comparison.

Already, both sides have made considerable progress in resolving many of the technical problems associated with this space flight mission. In addition, Soviet officials have agreed to consider the U.S. request for its TOMS personnel to visit all the TOMS/Meteor-3 related facilities in the U.S.S.R. including test/integration, technical position of the launch site, and ground station facilities.

TOMS also has been accepted as part of the Phase B study for the Japanese Advanced Earth Observation Satellite (ADEOS), proposed for flight in 1995. In addition, a TOMS is planned for flight on one of NASA's Small Explorer low equatorial orbit Earth Probes, scheduled to begin during the early 1990s to supplement data collected from the instruments aboard the EOS space platforms.

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5

Cloud Climatology and the Radiation Budget

In 1988, the International Satellite Cloud Climatology Project (ISCCP), the first project of the World Climate Research Program (WCRP), completed its fifth year of data collection. ISCCP has since been extended to 1995. This project is designed to produce a 12-year satellite global radiance and cloud data set. The program is sponsored by the International Council of Scientific Unions (ICSU) and the World Meteorological Organization (WMO). NASA's Goddard Space Flight Center Institute for Space Studies serves as the Global Processing Center for the ISCCP.

The processing of the basic radiance imaging data sets gathered from all of the world's operational weather satellites (with the exception of the Indian National Satellite [INSAT]) had been completed through 1985, with some satellite data sets completed through 1987. However, normal data processing was interrupted by the discovery of anomalies in the infrared calibrations, in particular, daily variations in the heating-cooling cycles of the geostationary satellites. All of the data through 1984 have now been re-calibrated and normal processing of the radiance data sets has resumed. Processing of radiance data through 1988 was completed late in 1989.

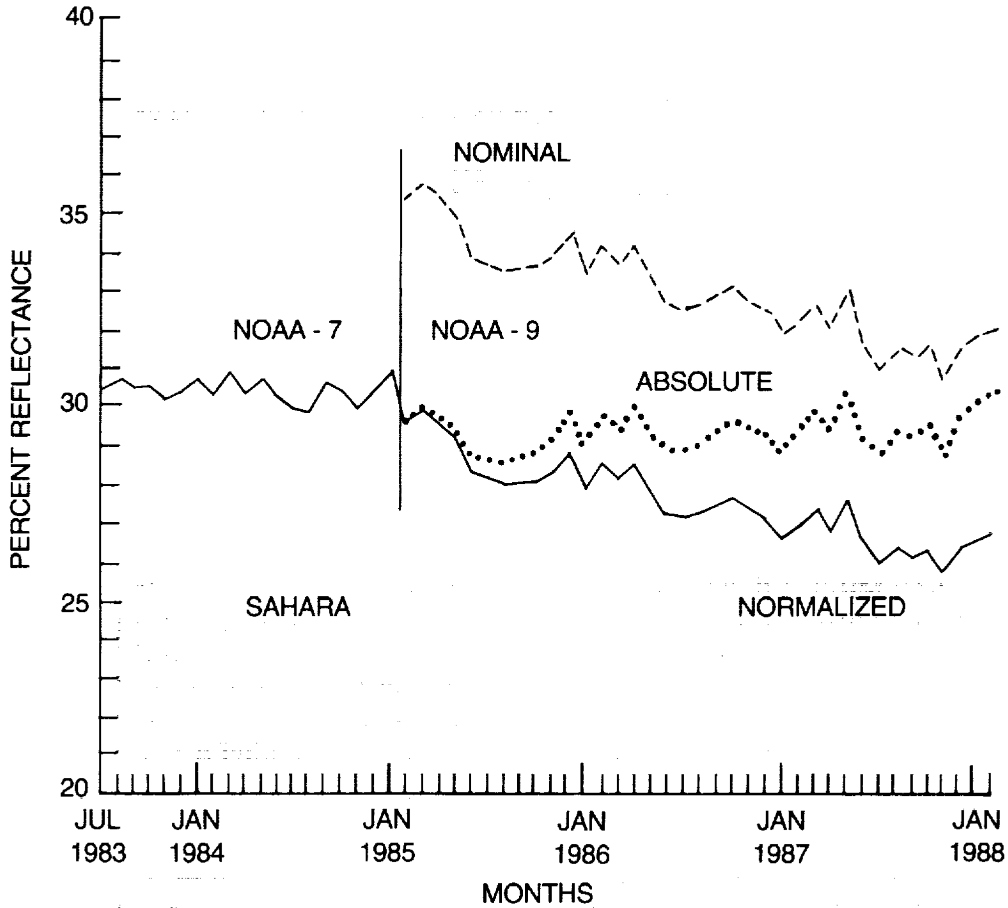
A major accomplishment has been the establishment of the first comprehensive absolute calibration for the visible radiance channels on all the NOAA polar orbiting weather satellites. A combination of the ISCCP calibration monitoring results was used along with three NASA/NOAA ER-2 flights to calibrate the Advanced Very High Resolution Radiometer (AVHRR). Figure 5-1, Surface Mean Visible Reflectance ISCCP Calibration Tables, illustrates the ISCCP normalization of visible radiance measurements for two polar orbiters by showing the measured surface reflectance for the Sahara desert. This illustration depicts the time history of the visible radiance measurements over this desert from NOAA-7 and NOAA-9 satellites from July through February 1988. Nominal calibration refers to the original calibration based on pre-launch laboratory measurements of instrument performance—the only calibration information that is normally available. Normalized calibration refers to the change in the NOAA-9 calibration to produce conformity with the NOAA-7 measurements during a 3-week period of overlapping observations. The absolute calibration is obtained by removing an apparent trend in observed radiances over the whole Earth.

The difference between the NOAA-7 and NOAA-9 nominal calibrations reveals the uncertainty of the post-launch calibrations. The NOAA-9 normalized curve indicates the effect of adjusting NOAA-9 to agree with NOAA-7 during a 3-week period of overlapping observations in January 1985. Finally, the NOAA-9 absolute curve shows the effect of removing the long-term drift in the calibration. These adjustments have been performed for NOAA-8 and are being extended to cover NOAA-10 and NOAA-11.

Since ISCCP radiance data normalization has been achieved for all operational satellites, a calibration standard for the narrowband imaging data (visible and infrared) is now available. This calibration standard allows these data to be used quantitatively in long-term climate monitoring and analyses for the very first time.

The ISCCP cloud analysis procedure represents the first comprehensive global, multi-satellite data analysis system ever implemented. Imaging data from up to six satellites, temperature/humidity profiling data from two satellites, conventional weather observations from around the world, and additional

FIGURE 5-1. **SURFACE MEAN VISIBLE REFLECTANCE ISCCP CALIBRATION TABLES**



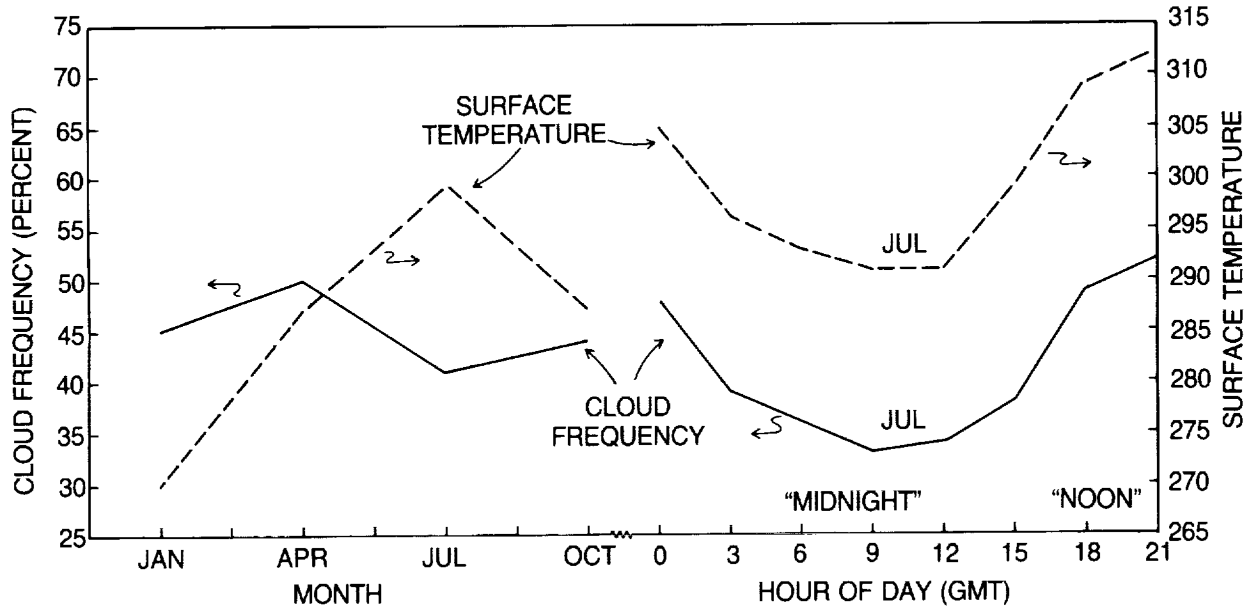
surface data are all combined into a single, global analysis.

In 1987, early versions of the cloud products were distributed to the science community to determine which parts of these data would be most useful for research. Full production of the global cloud products began in 1988, and the first 12 months' results have been archived. Figure 5-2, Seasonal and Diurnal Cycles of Cloudiness and Surface Temperature Over Continental United States, illustrates some early results from these data by showing the seasonal and (summer) diurnal variations of cloud amount with surface temperature for the continental USA. The seasonal variation of total cloud amount and surface temperature is illustrated by the monthly mean results inferred from the ISCCP analysis for July 1983, January 1984, and April 1985. The diurnal variations are from July 1983, where the values at each Greenwich Mean Time are monthly averages. The approximate times of local midnight and noon are indicated.

Figure 5-2 shows that on a daily basis in summer, cloudiness increases in the daytime in response to convective activity over the hotter land. On a seasonal basis, the rapid change of temperature associated with the change of seasons, produces more storm-related cloudiness.

A special data set has been produced for April 1985 to support intensive comparisons with coincident ERBE radiation flux measurements and comparison of both the cloud and flux data with weather-forecast and climate General Circulation Models. Studies are also being conducted to determine methods for inferring the radiation fluxes at the surface from satellite data using special ISCCP products and other data sets collected during the first ISCCP Regional Experiment (FIRE) Cirrus Intensive Field Observations (see below) in October 1986. These studies will increase our understanding of the role of clouds in determining the radiative energy exchanges on Earth.

FIGURE 5-2. **SEASONAL AND DIURNAL CYCLES OF CLOUDINESS AND SURFACE TEMPERATURE OVER CONTINENTAL UNITED STATES**



Project Fire

Project FIRE (First ISCCP Regional Experiment) is a U.S. cloud climatology research program that was initiated in 1984 to study those clouds which have a major impact on the Earth's global climate. Specifically, FIRE has measured the radiative and physical properties of two types of clouds: cirrus, and marine stratocumulus, over the continental U.S. Measurements have been taken from a variety of satellite, airborne, and surface platforms over several space and time scales. These observations are being used to verify and improve the satellite retrieval techniques of the ISCCP and to achieve realistic characterizations of clouds for climate models.

An unprecedented set of airborne, surface-based, and satellite measurements of the microphysical, mean, turbulent, and radiative properties of cirrus and marine stratocumulus clouds has been collected. Researchers face the major challenge of integrating and synthesizing the analyses of these data in order to describe and explain the complicated structure of these two cloud systems. The regional, multi-year data of the Extensive Time Observations (ETO) will be used to bridge the temporal and spatial scale gap between the Intensive Field Observations (IFO) and ISCCP data.

Data analysis is on schedule and the processing of individual sensor data from both experiments essentially complete. Intercomparisons have begun of data from different sensors, of sensor data with models, and of sensor data with ISCCP cloud parameters. Both statistical and model-based analyses are in progress along with efforts to develop and improve Global Circulation Model (GCM) parameterizations.

Results from analyses of cirrus and marine stratocumulus observations were presented at the FIRE Science Workshop held in Vail, Colorado, in July 1988. Over 100 presentations were given on the Cirrus IFO and ETO, and on efforts to build models. Some of these results are as follows:

- The cirrus clouds exhibit a complex structure both vertically (multi-layered with both top-down and bottom-up generation processes) and horizontally (over meso-, synoptic, and planetary scales).
- The amount, size, shape, and crystal formation of the cirrus ice crystals are markedly different than previously thought, and should be accounted for in any breakdown of cloud components. Smaller cirrus crystals (less than 30 microns) dominate radiative properties, even when larger crystals (200–100 microns) dominate the cloud ice-water content.
- Comparisons of GOES/VAS CO_2-slicing cloud height retrievals compare well with lidar-observed cirrus altitudes.

- For marine stratocumulus clouds, the atmosphere above and within the marine boundary layer exhibits complex structure, in both clear and cloud regions (see Figure 5-3).
- Aerosols, liquid water, and cloud structure affect the reflectivity of solar radiation from marine stratocumulus clouds—important features that should be incorporated in any realistic cloud description.
- Broken clouds reflect 12 percent less solar radiation than solid overcast clouds.

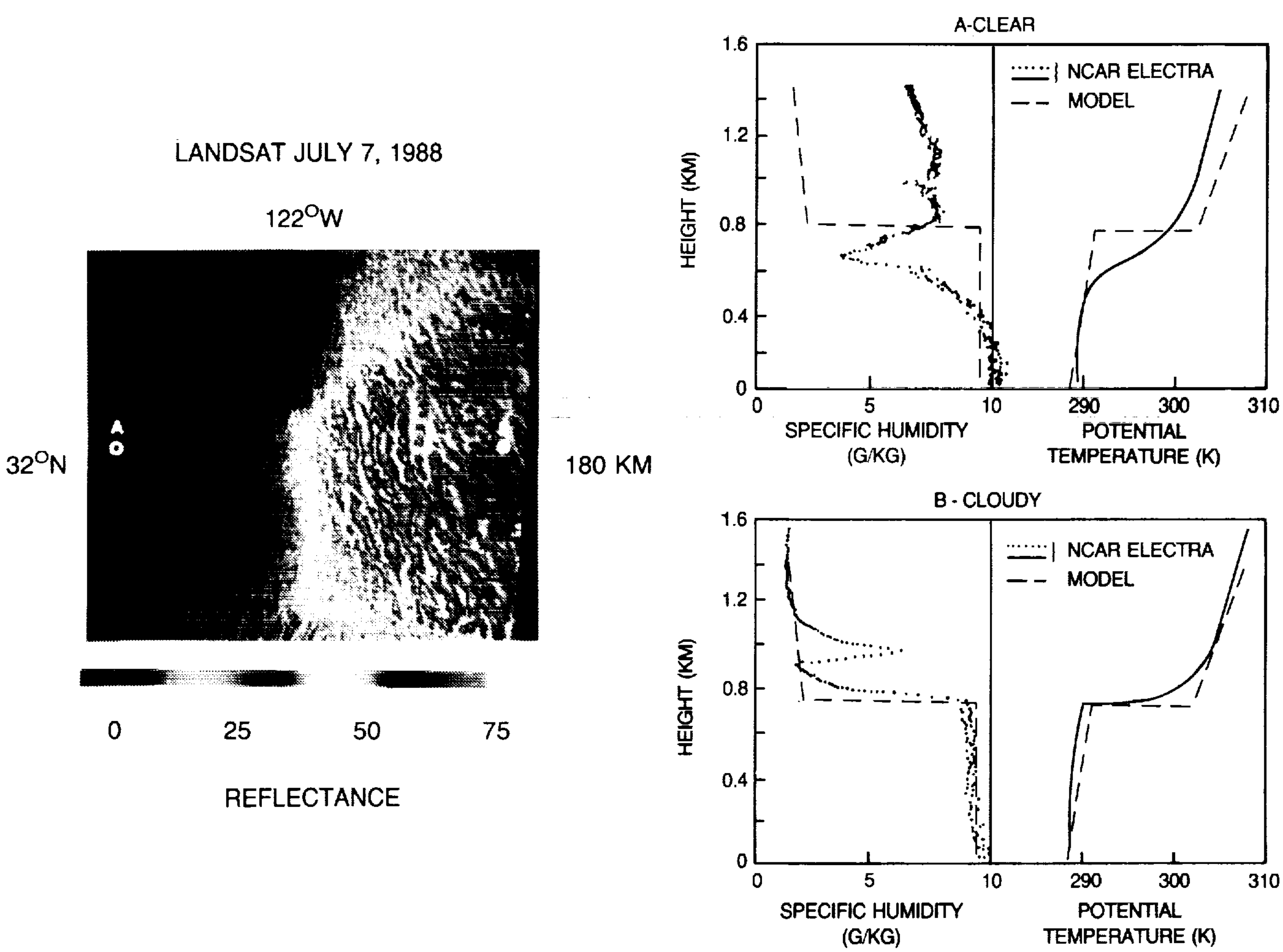
At present, FIRE researchers are analyzing a larger amount of cloud data than ever collected before from three major data-gathering components:

- The Cirrus IFO, in central Wisconsin in October 1986
- The Marine Stratocumulus IFO, off the southwest coast of California in July 1987
- The ETO, collected at several sites in the continental United States since April 1986

Future Plans

Planning for a second phase of FIRE is under way. In October and November 1988, planning workshops were held on the cirrus and marine stratocumulus, respectively. Science objectives, experiment locations and times, and potential instrumen-

FIGURE 5-3. **FIRST ISCCP REGIONAL EXPERIMENT (FIRE): Marine Stratocumulus Intensive Field Observations, July 1897**



tation and platforms will be summarized in separate science plans. These plans will be combined as an Omnibus Proposal and submitted to the supporting agencies (NASA, the National Science Foundation [NSF], Office of Naval Research [ONR], Department of Energy [DOE], Air Force Geophysics Laboratory [AFGL], and the National Oceanic and Atmospheric Administration [NOAA]) for their consideration. The plans will address the remaining science objectives of FIRE and take advantage of lessons learned from the first IFOs.

Preliminary indications are that a mid-latitude cirrus cloud experiment will be conducted in Kansas in late fall 1990, and a tropical cirrus cloud experiment in the vicinity of Kwajalein, Marshall Islands, in late 1991 in conjunction with the TOGA/COARE (Tropical Ocean Global Atmosphere Program/Coupled Oceans Atmosphere Response Experiment). The Atlantic Stratocumulus Transition Experiment (ASTEX), the marine stratocumulus IFO component of FIRE II, will be conducted in the vicinity of the Azore Islands in late spring 1992. The Office of Naval Research will be the lead agency for ASTEX.

The Earth Radiation Budget Experiment (ERBE)

Studies of the Earth's climate and climatic changes have been hampered by insufficient information on the planet's radiation balance, i.e., the relation between incident solar energy, reflected solar energy, and energy emitted from Earth. The Earth Radiation Budget Experiment (ERBE) is reducing this serious gap in our knowledge by compiling a comprehensive long-term database on the Earth's radiation budget since 1984. ERBE investigations have included:

- The monthly average radiation on regional, zonal, and global scales
- Variances in the absorption of solar radiation by the oceans, sea ice, tropical forests, deserts and other geographic features in accordance with the zenith angle of the Sun and with the seasons
- Cloud modulation of the absorption of solar radiation in various regions of the Earth

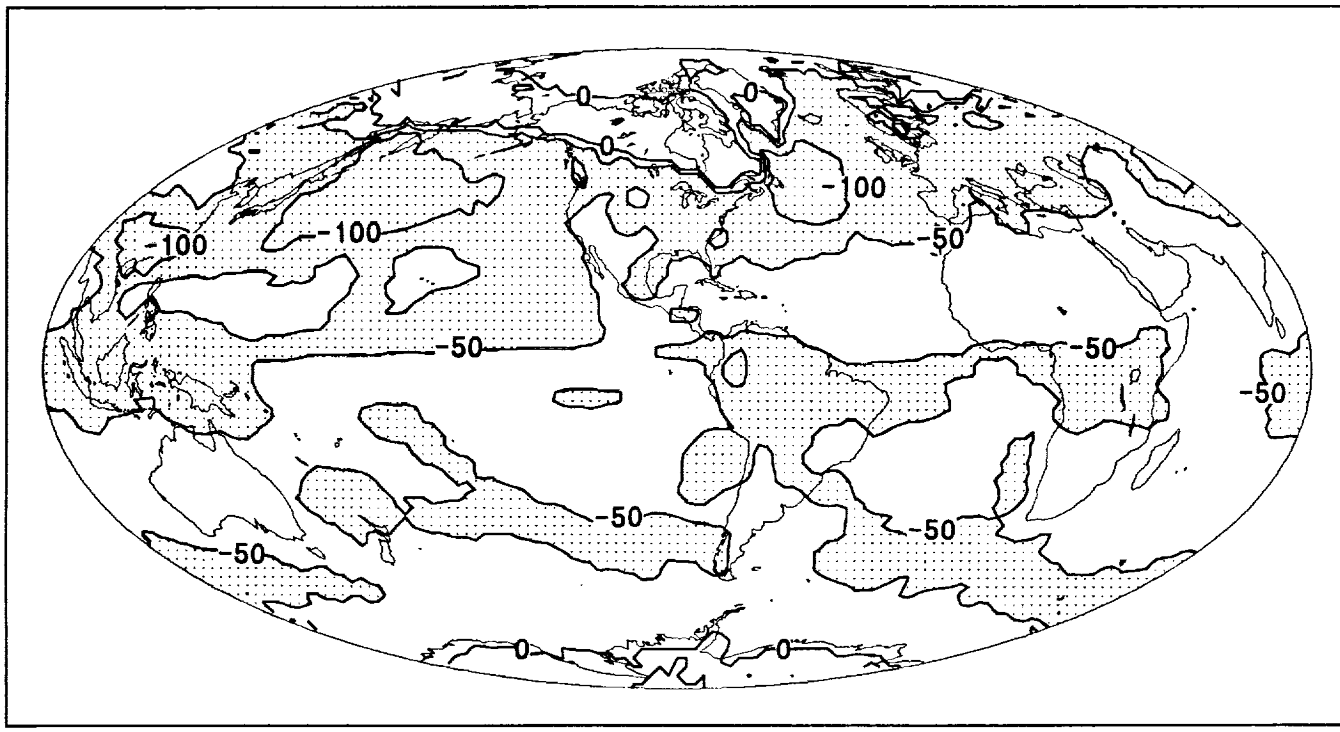
The Earth's climate and weather are strongly influenced by incident solar radiation, which is both reflected away from and absorbed by the Earth and its atmosphere, and by such factors as clouds, which influence the extent of this radiation. Climate is a complex function of the gradient between the surplus or deficit of radiation energy at the tropics and poles, respectively; the relative strengths of the several energy transport processes; and the interaction between these transport processes.

Clouds have a significant influence on the radiation balance. They cover about half of the Earth, doubling the proportion of sunlight reflected back into space to about 30 percent. This reflection by clouds might be expected to have a cooling effect on the Earth's climate. However, clouds not only can block incoming, shortwave radiation from the sun, but also the longwave, infrared radiation emitted by the warmed air and surface of the Earth beneath them. By trapping longwave radiation, clouds can produce a warming effect on the Earth's climate (a greenhouse effect) that tends to counteract their reflectivity. Modulation by clouds of the clear sky solar and longwave radiation fluxes have been characterized as cloud-radiative forcing.

Prior to ERBE, there had not been enough high spatial resolution observations around the globe for researchers to know whether today's clouds cooled or heated the Earth. A study by one group of investigators based on observations by two ERBE satellites during April, July, and October, 1985, and January 1986, has provided the first evidence that the clouds of today's climate cool the Earth below the temperature it would be without clouds. This is because the shortwave cloud forcing that produces a cooler climate is greater than the longwave cloud forcing averaged over the entire planet. For example, during April 1985, clouds around the globe reduced absorption of incoming solar radiation (340 watts per square meter [W/m^2]) by 44.5 W/m^2 while reducing infrared losses to space by 31.3 W/m^2. That process produces a net reduction of 13.2 W/m^2 in the radiative heating of the Earth. (See Figures 5-4–5-6 in which data from SCANSCAT on board ERBS and NOAA-9 have been combined.)

Although this study found that clouds now cool the Earth's climate, this situation may not last if global warming from increased anthropogenic trace gas emissions continues. It is not yet known how the radiation balance would shift under these conditions, but model studies suggest that if the planet continues to get warmer, clouds might have a different effect on the climate. Current climate models predict that an instantaneous doubling of CO_2 emissions would warm the Earth from about 3° to 5°C through an increase in net radiative heating of only 4 watts per square meter.

FIGURE 5-4. **SHORTWAVE CLOUD FORCING – ERBS + NOAA-9, APRIL 1985**



SW cloud forcing shows peaks in the mid-latitudes. It is also large north of 30° North in the Atlantic and Pacific oceans where the reduction of absorbed solar radiation as a result of clouds exceeded 100 W/m^2.

However, it is now believed that changes in global cloudiness, even as small as a few percent, could possibly have an even more significant impact on the global climate than increased emissions of such greenhouse gases as CO_2. The negative cloud-radiative forcing is 3–5 times as large as the doubled CO_2 forcing, thus possibly counteracting the warming effect of the greenhouse gases.

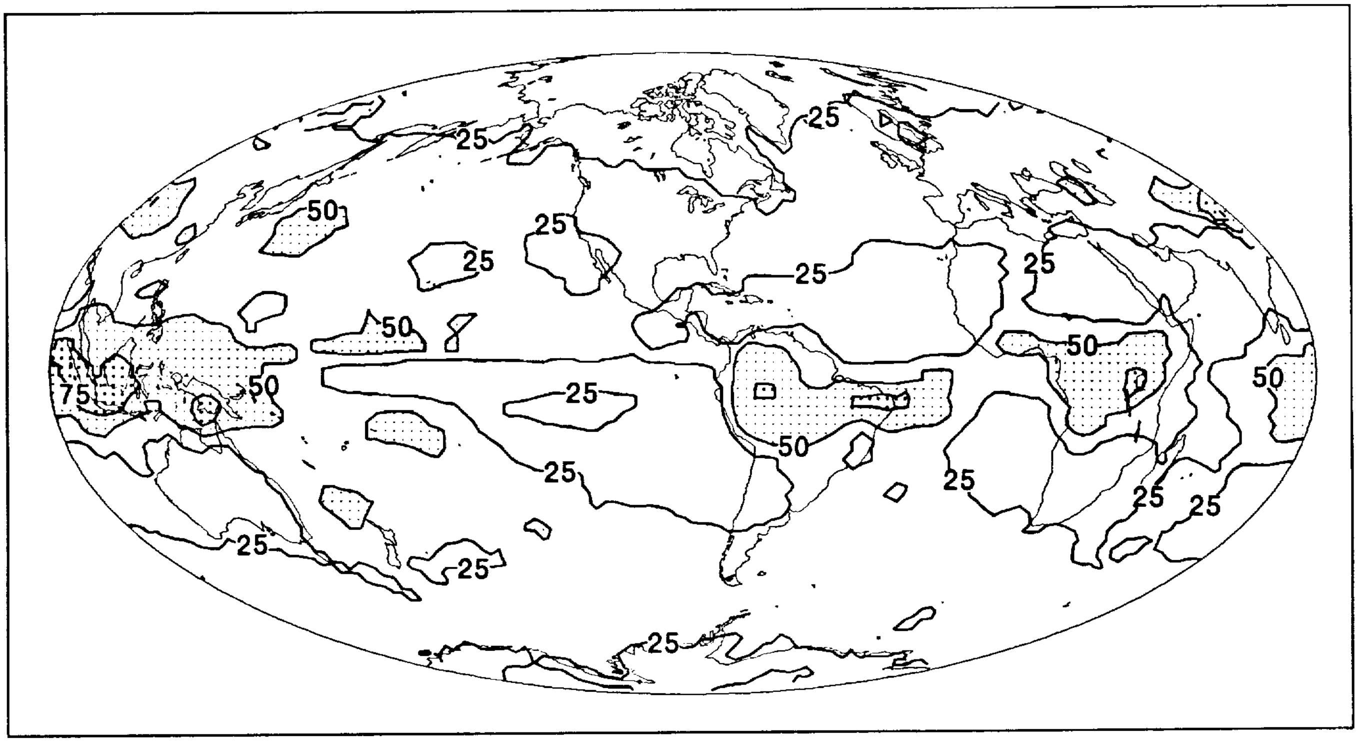
While General Circulation Model (GCM) studies have enhanced our understanding of cloud-climate interactions, before ERBE there was no global perspective on these interactions. Data from ERBE observations are helping investigators to create improved global climate models that recognize the complexities of cloud-climate interactions and the impact on these interactions of natural and human forces—especially greenhouse gases. Thus, researchers will be able to estimate more accurately the impact of clouds on climatic variability worldwide. ERBE data on the climatic effects of clouds will also help scientists assess the impact of clouds on any warming of the Earth.

ERBE represents a major improvement over previous studies because:

- The program provides greater global coverage than previous missions by using three spacecraft, the NOAA-F and NOAA-G TIROS-class operational meterological satellites and NASA's Earth Radiation Budget Satellite (ERBS). Diurnal cycle observations from instruments aboard these satellites not only minimize time-sampling errors but also systemic biases existing in earlier measurements. Moreover, diurnal measurements yield critical insights into climate feedback processes involving the land surface, meteorology, and solar heating.

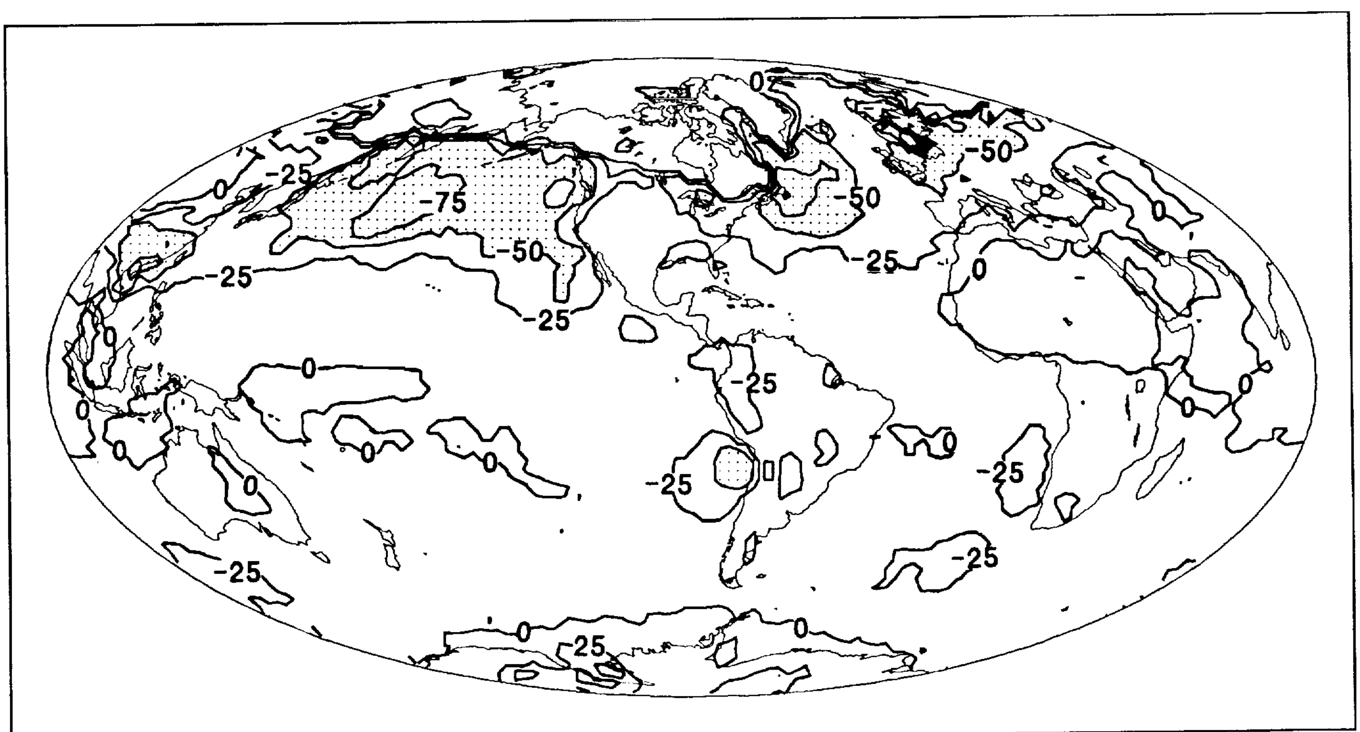
- More accurate measurements than those of previous missions have been made possible by highly sophisticated instruments. Each of the three satellites carries a set of ERBE scanner and non-scanner radiometers (ERBE-S and ERBE-NS) for measuring incident solar energy, reflected solar energy, and the Earth's emitted radiation. In addition, NASA's ERBS carried the Stratospheric Aerosol and Gas Experiment (SAGE II), which measures solar radiation attenuation caused by atmospheric properties and the distribution of aerosols and gases in the atmosphere. These measurements yield data that can be used to determine the effects on

FIGURE 5-5. **LONGWAVE CLOUD FORCING – ERBS + NOAA-9, APRIL 1985**



The LW cloud forcing reaches peak values over tropical regions and decreases towards the poles. In general, clouds reduce the LW emission to space.

FIGURE 5-6. **NET CLOUD FORCING – ERBS + NOAA-9, APRIL 1985**



In tropical regions, the LW and SW terms nearly cancel each other. Negative forcing is particularly large over the Pacific and Atlantic oceans (between −50 and −100 W/m^2).

climate and weather of atmospheric constituents of the radiation budget.

- ERBE's preflight and onboard calibrations greatly enhance the accuracy and precision of the measured radiation.

Much remains to learned about the relationship between clouds and the Earth's climate as it is influenced by natural and human processes. Researchers face the important challenge of creating climatic models to illustrate the complex feedback mechanisms that determine cloud type, cloud cover, and how clouds affect the global climate. As the Earth becomes warmer, cloud cover, altitude, proportion by type, and liquid water content could all change and in the process, alter the radiative fluxes in and out of the climate system.

ERBE is thus making a major contribution to our understanding of the influence of cloud-radiation interactions on the global climate and of their role in climatic change. This experiment is stimulating the development of more comprehensive climatic models able to predict changes in the Earth's climate with greater accuracy.

6

Studies of Ocean Color

Studies of the world's oceans from space have contributed significantly toward greater scientific understanding of the global environment. Between 1978–86, the Coastal Zone Color Scanner (CZCS) aboard NASA's Nimbus-7 satellite has provided revolutionary data on the world's oceans by imaging ocean color on a global scale. The technique of ocean color imaging was developed primarily at the Goddard Space Flight Center and the University of Miami. This technique has enabled oceanographers to see the global distribution of photosynthetic organisms in the world's oceans for the first time.

CZCS images have shown that the ocean has a far more significant role in the global carbon cycle than previously estimated, and is crucial to our understanding of how the Earth's climate is likely to change in the future. By recording 68,000 two-minute ocean scans over its 8-year mission lifetime, the CZCS has laid the foundation for further systematic studies of ocean color from space during the 1990s. Global datasets from this instrument were published in 1989.

The image on the front cover of this report shows the first truly global view of the Earth's biosphere. The composite image of the ocean chlorophyll concentration was produced from 31,352, 4-km resolution CZCS scenes from November 1978 through June 1981, each of which corresponds to approximately 2 million square kilometers of ocean surface. Nearly 400 billion bytes of raw CZCS data located on more than 12,000, 9-track computer tapes were used to make this image. Land vegetation patterns are derived from 3 years of daily images from NOAA-7's visible and near infrared sensors.

CZCS images have revealed much more global variation and dynamic changes in ocean color than had previously been imagined. These findings are important because the color of the sea is directly linked to its biological productivity, which is reflected by concentrations of pigments derived from living phytoplankton—microscopic single-celled aquatic plants that are at the base of the marine food chain. Hence variations in the color of the sea are the result of variations in concentrations of phytoplankton.

Phytoplankton play a vital role in the global carbon cycle because they remove atmospheric carbon dioxide (CO_2) that has been dissolved in sea water, and convert it into organic matter during the process of photosynthesis. A considerable proportion of that organic carbon eventually sinks to deep ocean waters. This creates a deficit of CO_2 in the upper layers of the ocean, which is then replenished by the ocean's absorption of more CO_2 from the atmosphere. Phytoplankton are therefore a major sink for atmospheric carbon dioxide.

It is essential to understand how this "biological pump" works in order to predict how concentrations of carbon dioxide in the atmosphere might change over the next few decades. Due to the widespread presence of phytoplankton, the world's oceans function as a huge carbon reservoir, thus having a major role in any global climatic changes. In addition, concern about the global greenhouse effect has made the study of the oceanic carbon cycle even more urgent.

CZCS measurements of ocean color have revealed for the first time the global variation in the phytoplankton concentrations and the rate at which these plants photosynthesize carbon (primary productivity). Since phytoplankton pigments absorb energy in the red and blue regions of the spectrum and reflect green light, satellite measurements of ocean radiance at selected wavelengths can be used to estimate phytoplankton concentrations and thus the extent of upper ocean level primary productivity.

Phytoplankton play a key role in the global biogeochemical cycles of carbon and other elements critical to marine and terrestrial life. They not only transform CO_2 into sugars and other simple organic molecules and release oxygen, as previously mentioned, but also use nitrogen, phosphorus, and silicon among other nutrients, for example, to produce proteins.

CZCS observations have vastly improved understanding of processes that control primary production in the ocean and the important part oceanic organisms play in the global carbon cycle. Results of these observations include:

- The demonstration of the geographic extent of spring "blooms" of phytoplankton in coastal waters at temperate latitudes and increased knowledge of the factors responsible for these phenomena. These spring blooms are major events in the North Atlantic Ocean, in the polar seas, and in temperate coastal waters worldwide. They occur after deep water rich in nutrients has been brought to the surface by winter storms and been exposed to warmer water and more sunlight during spring. This process explains the extent to which the ocean influences the global carbon cycle because a large proportion of the phytoplankton associated with these spring blooms sink rapidly to the deep ocean waters which do not again reach the surface for thousands of years.

- The first real-time map of near surface chlorophyll concentrations through imagery of phytoplankton blooms in coastal waters: CZCS image sequences have been used to investigate the timing and duration of phytoplankton blooms and to track the movement and persistence of ocean features, thus significantly increasing our knowledge of ocean dynamics. Further research will emphasize use of CZCS imagery to study phytoplankton dynamics on ocean basin and global scales. By combining the results from many orbits to produce a composite image, CZCS chlorophyll maps of entire basins and of the global ocean can be constructed.

- The mapping of global concentrations of phytoplankton and seasonal changes in these concentrations in such areas as the Atlantic and Pacific Oceans and off the west coasts of Africa and Peru.

- The revelation of an important concentration of phytoplankton along the Equator through a clearly defined line of color. Phytoplankton flourish along the Equator because of the outward flow of surface water toward both the north and south poles, causing deep nutrient rich water to rise and replace the water flowing poleward. This finding confirms the importance of the equatorial ocean in the global carbon cycle.

- The identification of significant differences in the seasonal production of phytoplankton between the Arctic and Antarctic, because the northern ocean is surrounded by land while the southern ocean surrounds land.

Satellite ocean-color imagery can also be used to estimate primary productivity over relatively large areas. However, space imagery must be complemented by observations from ships because it only yields chlorophyll estimates for the upper layers of the ocean, thereby omitting the primary productivity occurring in deeper waters.

These findings have demonstrated the need for further studies of the world's oceans from space prior to the EOS space flights in the late 1990s. To meet this requirement, NASA is considering a successor to CZCS in the early 1990s. Sea-WiFS, with twice the number of spectral bands and radiometric sensitivity as the CZCS, would be able to provide improved estimates of phytoplankton concentration, oceanic absorption of carbon, and other important processes. The scientific objectives of the proposed mission include:

- establishing the mean rate of primary productivity and its variability in the world's oceans based on color images of phytoplankton processes and concentrations

- quantifying the oceanic portion of the global cycles of carbon and other elements and trace gases important to global biogeochemistry and oceanic biological processes, and how the oceans affect, and respond to, changes in global biogeochemical and climate processes

- investigating and monitoring coastal ocean processes, in particular human impacts on the coastal zone, and advancements in fisheries science, resource utilization, and management.

The Sea-WiFS mission would greatly benefit studies of the Earth system and of global change by yielding a more accurate picture of the relative contributions of land masses vs. oceans toward the global carbon budget. By providing data for a more precise definition and estimate of the extent of oceanic carbon transformations, the Sea-WiFS would help scientists obtain a more accurate idea of how much terrestrial ecosystems contribute toward the global carbon budget. Scientists could then determine whether terrestrial ecosystems are a net source or sink for atmospheric carbon. In addition, improved understanding of phytoplankton growth and abundance from Sea-WiFS observations would provide a more precise view of the source and sink functions for several important atmospheric gases (especially dimethyl sulfide and nitrous oxides), which are produced primarily by oceanic biological processes. Moreover, scientists would learn more about the extent to which anthropogenic sulfur emissions versus gases from natural sources contribute toward the quality of the atmosphere.

Sea-WiFS would provide the large scale observations required by the Joint Global Ocean Flux Study (JGOFS), a massive multinational collaborative project involving West Germany, Britain, Canada, the Netherlands, the United States, Japan, Peru, Chile, Australia, Taiwan, the Peoples' Republic of China, Korea, the U.S.S.R., France, and Sweden, and now a "core program" of the International Geosphere-Biosphere Program (IGBP). JGOFS, which is expected to last at least 10 years, is aimed at understanding and predicting the fluxes of carbon and other biological elements in the global oceans and the types of exchanges they have with both the atmosphere and the deep sea.

Other international studies of the world's oceans to which the Sea-WiFS could contribute include the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean Global Atmosphere Programme (TOGA). Further oceanic studies are also planned by Japan's space agency NASDA which wants to fly an Ocean Color and Temperature Sensor (OCTS) on its ADEOS satellite in 1996.

Data from these space missions would be rapidly distributed to the global oceanographic community in a form that would enable members to integrate satellite instrument information with both field observations and mathematical models.

7

Global Tropospheric Chemistry Studies

NASA's Global Tropospheric Experiment (GTE) investigates the changes that are occurring in the composition of the lower atmosphere, the troposphere, that part of the atmosphere most sensitive to changes across the Earth's surface. Results to date have been dramatic, unexpected, and very enlightening.

Latest Results

GTE/ABLE (Atmospheric Boundary Layer Experiment) missions have produced a wealth of data which are changing our view of the biosphere/atmosphere interaction, the relative importance of various ecosystems in driving atmospheric chemical change, and the reliability of model projections of atmospheric chemistry/global change connections. Some startling differences from predicted behavior have been detected.

The first phase of the latest GTE/ABLE mission, GTE/ABLE-3A, took place over the Arctic from bases in Alaska during July and August, 1988. Investigation of these northern regions is important because they are major sources of tropospheric CH_4. In addition, analysis of tropospheric CO_2 in Alaska has revealed substantial biospheric and meteorological influences on concentrations of this primary greenhouse gas. Surface deposition on vegetation and snow cover is known to be an important sink for O_3 at high latitudes, and the Arctic is close to major northern American anthropogenic sources of trace gases and aerosols.

During 1989, analyses of the ABLE-3A results indicate some highly significant findings. These include:

- **Methane flux from the Alaskan ecosystem.** A unique combination of measurement techniques produced, for the first time, a direct measurement of methane emissions from remote Arctic terrain on a regional scale.
- **Alaskan methane flux and global warming feedback effects.** ABLE-3A confirmed that the Alaskan wetlands are a significant source of methane from plant decay, emissions that increase dramatically with increased soil moisture. Any warming global trend would thus give rise to a rapid increase in the flux of methane to the global atmosphere.
- **The Arctic as a sink for nitrogen**. Biologic processes in the Arctic remove important trace nitrogen compounds from the atmosphere, leaving very low levels of nitrogen oxides in the lower and middle regions of the Arctic troposphere. These low levels lead to net photochemical destruction of ozone in this region.

Study of the Arctic troposphere also provides a good picture of atmospheric photochemistry in a clean atmosphere, and a baseline for understanding the changed photochemistry of a polluted environment.

Early results from the vast quantity of data from the GTE/ABLE-2 campaign also show some notable trends. This experiment was conducted in two phases, in 1985 and in 1987, in order to obtain data on both the wet and dry seasons over the Amazonian rain forest. Analysis of results to date indicates:

- **Degradation of the air quality over the Amazonian region during the dry season when forest burning takes place**. Trace gas amounts reach levels usually found only in industrial regions.
- **A disappearing tropospheric ozone sink**. While an undisturbed rain forest is a highly efficient ozone sink, absorbing 5 to 50 times more ozone than previously measured pine forest or water surface, forest depletion will drastically reduce this capability.

- **The potential for changes in atmospheric circulation**. Such changes may occur as the rain forest is cut back and convective storms diminish.
- **The positive feedback mechanism of biomass burning as a source of greenhouse gases**. In addition to increases in carbon dioxide, forest burning can increase ozone production significantly.
- **Globally significant methane emissions**. About 12 percent of the estimated worldwide methane emissions come from wetland sources.

Taken together, the results from the ABLE-2 and ABLE-3A expeditions show remarkable and unexpected patterns in tropospheric composition on a hemispheric scale.

The most recent GTE/CITE (Chemical Instrumentation Test and Evaluation) mission, GTE/CITE-3, was conducted over Wallops Island, Virginia and over areas of the tropical Atlantic Ocean from Natal, Brazil, in late summer of 1989. This mission focused on compounds important in the sulfur cycle of the global atmosphere. Sulfur compounds are an indicator of biological activity, particularly over productive parts of the oceans. CITE-3 intercompared techniques used in previous field studies to help assess the validity of the existing sulfur chemistry database, and to guide the development of the next generation of instruments. In 1990, efforts will focus on detailed data analysis of the CITE-3 campaign.

Background

In 1984, the National Academy of Sciences (NAS), recognizing the central role that the troposphere plays in global change, recommended a national research program in tropospheric chemistry as part of a larger, international effort—the Global Tropospheric Chemistry Program (GTCP). Against that background, NASA's GTE was designed to bring the advanced instrumentation, major facilities, large-project management experience, and atmospheric research expertise of NASA to bear on the important objectives of the GTCP. GTE projects include advanced instrument development, large-scale field measurements from large aircraft, and space observations.

The most extensive experiments examine the nature of the interaction between the biosphere and the atmosphere. These GTE/ABLE projects study the fluxes of gases between the free troposphere and the atmospheric boundary layer, the part of the troposphere nearest to the surface of the Earth, where the interaction is strongest. GTE/ABLE has so far carried out projects in the tropical Atlantic Ocean, the Brazilian rain forest, and the northern wetlands. These projects involve the study of the rate of exchange of material between the Earth's surface and the atmospheric boundary layer, and the processes by which gases and aerosols are moved to the free troposphere. In addition, a priority task has been the GTE/CITE Project, which undertakes the simulation, promotion, and development of new instrumental techniques and their validation and intercomparison onboard aircraft, backed up by ground- and space-based observations.

Earlier GTE Campaigns

The first GTE/ABLE mission, GTE/ABLE-1, which surveyed regions of the tropical Atlantic in 1984, produced a wealth of new data on the tropical ocean atmosphere exchange process and offered new insights into long range transport and its effects on remote ecosystems. Aircraft sampling off Barbados confirmed the significance of marine phytoplankton as a source of about one half of the natural sulfur emissions worldwide; examined air chemistry over tropical forests; and provided a startling view of the long-range transport of Saharan dust to areas over Barbados and its deposition in the tropical Atlantic Ocean.

The first CITE campaign, GTE/CITE-1, comprised one ground-based and two airborne experiments: over Wallops Island, Virginia in summer 1983; over the California coast and the Central Pacific in the autumn of 1983; and, in spring of 1984, over California and the southwest United States. The three experiments focused on measuring carbon monoxide (CO), nitric oxide (NO), and the hydroxyl radical (OH)—all critical trace gas components of atmospheric photochemistry with central roles in many potential global change issues. In 1986, GTE/CITE-2, over California and the eastern Pacific, focused on the intercomparison of instruments to measure components of the nitrogen oxide photochemical cycle. Few chemical cycles are more significant in potential global change than the nitrogen oxide cycle. CITE-2 was the largest field project ever mounted to assess the instrumentation and obtain data in conditions ranging from clean Pacific air to polluted continental air. The CITE-2 results confirmed that, in many cases, current atmospheric models do not adequately reflect the total reactive nitrogen species found in the troposphere. Given the central role these species play, and current limited understanding of tropospheric chemistry, the "nitrogen deficit" problem is likely to be a major focus of research and investigation for several years.

Future Missions

While interaction between the planet surface and the air will continue to be major thrust of the program, attention will turn increasingly to the characterization of the global distribution of tropospheric trace gases and aerosols and their relation to human activities globally. New aircraft- and space-based techniques will be important as will the need for a more international approach to addressing atmospheric chemistry research in the context of global change studies.

New long-range, high altitude aircraft-based experiments are being planned for the next decade, and the southern tropical Atlantic will be site of the first of these large-scale experiments. Next year, planning will be underway for the tentatively scheduled FY 1991 TRACE-A (TRansport and Chemistry near the Equator in the Atlantic) mission over the southern tropical Atlantic. This part of the ocean is tightly coupled to the natural sources and sinks of atmospheric gases in the tropical rain forests, and heavily affected by widespread biomass burning both in South America and in Africa, with sharp seasonal impact on tropospheric ozone concentrations.

A joint U.S.-Canada expedition, ABLE-3B, will be conducted in the summer of 1990 to cover the peatland and boreal forest region of northern Canada—in the world's largest continuous wetland area—to build on the data collected during the first phase of the Arctic campaign.

In addition, during FY 1990 preliminary planning will be undertaken on a potential GTE/PEM (Pacific Exploratory Mission)—a series of four projects to study atmospheric chemistry over the Pacific Basin. This region contains some of the cleanest air still to be found on Earth, but is also the region where some of the world's fastest-growing economies also are located. The region thus provides an important test-bed for investigations of the increasing effect of anthropogenic activities on the atmosphere.

8

First ISLSCP Field Experiment (FIFE)

The First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) was conducted on the Konza Prairie in Kansas during the summer of 1987. A follow-up experiment, FIFE-89, took place in 1989 over a period of 20 days from late July at the same location. The execution of FIFE-87 (as it is now known) was described in full in last year's Earth Science and Applications Division Annual Report, *The Program and Plans for FY 1988–1989–1990*.

The FIFE experiments are at the center of NASA's plan to develop a physically based approach to the use of satellite remote-sensing systems and a key component of ISLSCP. The general objectives of FIFE are a) to understand the biophysical processes controlling the fluxes of exchanges of radiation, moisture, and carbon dioxide between the land surface and the atmosphere; b) to develop and test methodologies for observing these processes in order to set up models for validation with satellite data.

The 1987 field phase of FIFE took place at and around the Konza Prairie Reserve on a 15-square kilometer area of grassland. About one third of the area is managed as a Long-Term Ecological Reserve for the study of grassland ecosystem dynamics. Sixteen automatic meteorological stations (AMS) were placed at the site in April-May 1987, and are still in operation. Flux stations were in place during the Intensive Field Campaigns (IFC). Distribution of both types of instrument was determined by a stratified sampling scheme.

The data acquisition of FIFE can be divided into two broad categories, the monitoring effort and the IFCs. The monitoring effort, which operated almost continuously through 1987, comprised the acquisition of AVHRR, Landsat, SPOT, and GOES satellite data, continuous acquisition of relevant meteorological data from the AMS, collection of gravimetric soil moisture surveys, streamflow data, biometric measurements, and observations of relevant atmospheric optical properties to study the effects of atmosphere on satellite remote-sensing images.

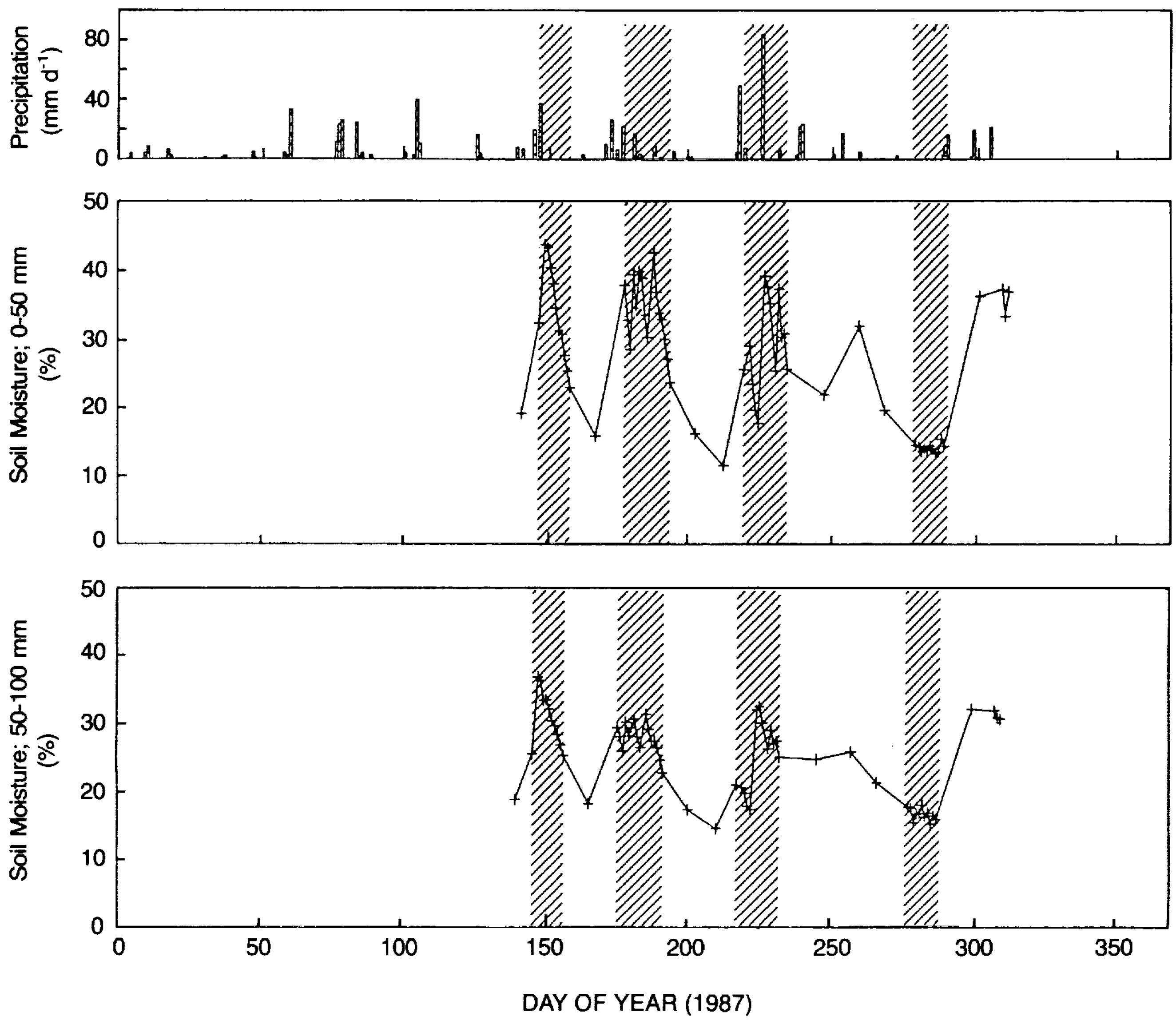
The IFCs were designed to acquire surface, airborne, and satellite radiometric and flux data together with biophysical and ancillary measurements to compare satellite data with surface conditions and fluxes. Each IFC was targeted at a separate phase of vegetative development: IFC-1—"greenup"; IFC-2—peak greenness; IFC-3 "dry-down"; and IFC-4 "senescence," but the unusual weather conditions produced very similar conditions of wet soils and green vegetation through the first three IFCs, and totally senescent vegetation cover and dry soil in IFC-4 (see Figure 8-1).

FIFE-87 Results

As yet, only a few direct comparisons between satellite and surface observations are available. A comparison between estimates of insolation and photosynthetically active radiation calculated from a simple atmospheric radiative transfer model driven by GOES satellite radiances, measured every 30 minutes, showed good agreement with surface observations.

A number of heat and moisture flux data sets were collected at different scales but at the same time. Figure 8-2 shows the midday evaporation ratio (latent heat flux divided by the sum of sensible and latent heat flux) as measured by airborne and surface eddy correlation techniques and as calculated from radiosonde data for one day in each IFC. Also shown are the NOAA-9 maximum NDVI values for the corresponding IFCs. The flux measurement techniques appear to agree fairly well and all capture the large

FIGURE 8-1. **PRECIPITATION AND SOIL MOISTURE CONDITIONS AT THE FIFE SITE DURING 1987**



drop in the evaporation ratio between IFC-3 and IFC-4.

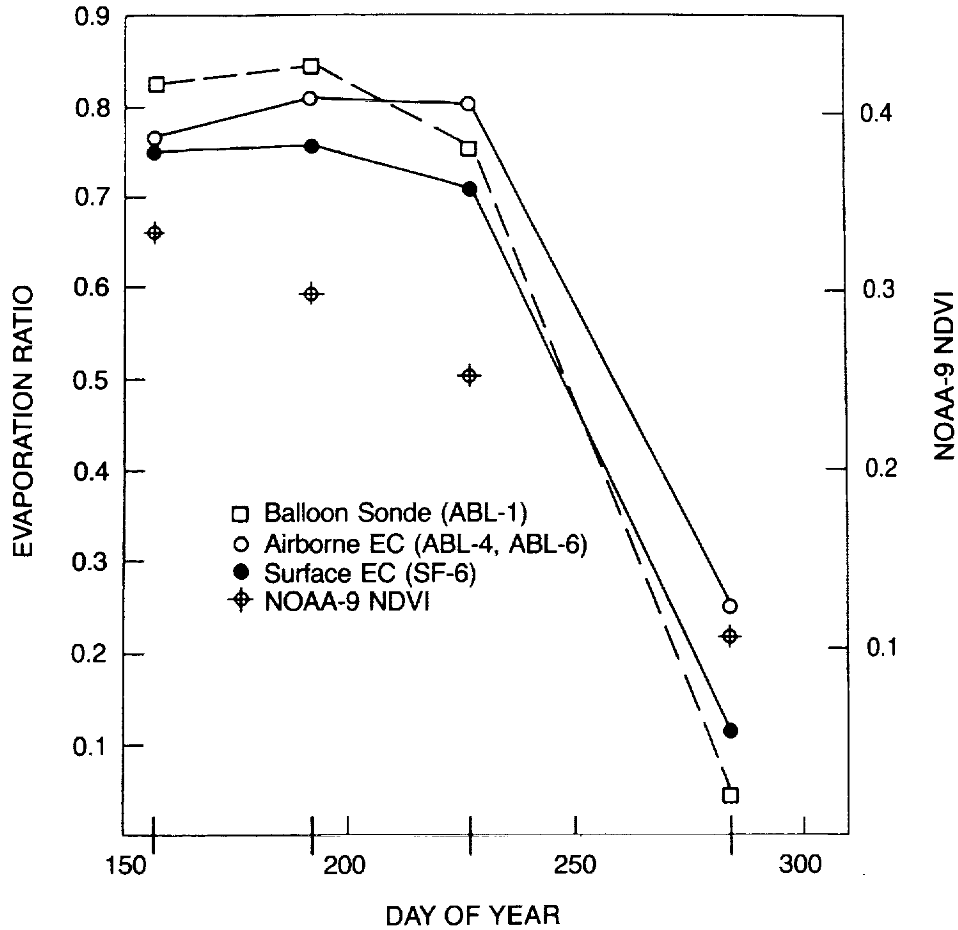
These and other results indicate that the FIFE data set should be adequate for testing satellite data algorithms; i.e., surface fluxes on large spatial scales can be computed from the field measurements and then compared with the output of surface energy balance models driven by satellite data.

FIFE-89

During the summer of 1987, unusually wet weather prior to and during the FIFE field campaigns limited the soil moisture throughout the test site to the middle-to-upper range of moisture conditions, which prevented observations when the strongest biological control would have been exerted on the evapotranspiration and photosynthetic rates.

FIFE-89 was conceived and designed to address this issue, and a number of additional experiment design issues uncovered by the analysis of the FIFE-87 data. The experiment was aimed at assessing how much of the carbon dioxide flux and evaporation emanated from the soil and the vegetation, and at obtaining improved *in situ* estimates of biophysical parameters relevant to the study of energy balance.

FIGURE 8-2. **MIDDAY EVAPORATION RATIO, FIFE-87**



The ratio was estimated using airborne and surface eddy correlation, flux measurements, and radiosonde data.

During the FIFE-89 experiment, the science team was able to observe the vegetated surface in a freely evaporating state with stress-free photosynthesis at the beginning of the experiment. An extended period of clear skies enabled a sequence of coordinated airborne remote sensing and flux measurement flights to be flown, in combination with intensive radiometric and flux measurement efforts at three supersites and 12 other flux stations under study within the FIFE area. Frequent airborne coverage was obtained both of soil moisture (through passive microwave measurements) and the vegetation state (with optical and thermal measurements). The instruments used included the aircraft Synthetic Aperture Radar (SAR), the L-band pushbroom microwave radiometer, the Advanced Solid State Array Spectrometer (ASAS), the Thematic Mapper Simulator (TMS), and the sun-tracking photometer.

The transition of vegetation from an unstressed to a stressed state was observed both spectrally and in terms of declining evapotranspiration and carbon exchange rates. Intensive surface, airborne, and spaceborne measurements were made at three subsites which had differing soil depths and soil moistures. The driest subsite was the first to enter stress, with the vegetation senescing over a period of a few days. Several days later it was followed by the next driest site, and finally the wettest subsite entered into senescence as the experiment ended. The intercomparison of these three sites, with similar vegetation but differing environmental parameters (soil moisture, evaporative demand, etc.), will provide a wealth of data for investigators who wish to understand the interaction of these biological and physical processes.

The campaign was conducted in conjunction with the National Science Foundation (NSF), the U.S. Department of Agriculture (USDA), the U.S. Geological Survey (USGS), and the National Oceanic and Atmospheric Administration (NOAA). As in FIFE-87, it included experimenters from France, Canada, and England. FIFE-89 also included nine Soviet scientists. Among other instruments, the Soviets used an instrument with very high spectral resolution, which had been flown on the Soviet's Mir space station. The Soviets will also be contributing satellite data from a conical scanner on Cosmos 1939 which has spectral bands similar to the AVHRR on the U.S. operational satellites. As part of this U.S./U.S.S.R. exchange agreement, U.S. scientists are expected to visit Kursk in the Soviet steppes in 1991.

Future Plans

Analysis of FIFE-87 data continues, particularly of the four "golden days" during which experimenters had the advantages of a satellite overpass (either Landsat or SPOT), during which the weather was exceptionally clear, and the aircraft sensors were operated throughout a full diurnal cycle.

A major symposium on FIFE-87 results will be held in February 1990 at the American Meteorological Society meeting in Anaheim, California. Towards the end of that year, a joint symposium is planned with the French-led HAPEX (Hydrological Atmospheric Pilot EXperiment) at the American Geophysical Union meeting.

9

Solid Earth Science Research Plan

In July 1989 NASA held a meeting at Coolfont, West Virginia, to design a recommended plan for NASA Solid Earth Science in the decade ahead. Over 100 scientists representing all aspects of the discipline were present together with representatives of the National Science Foundation (NSF), the U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), and from many international science agencies. The goal for this meeting was ambitious: to develop a program of research that would integrate the previously autonomous NASA Geology and Geodynamics Programs into a single NASA Solid Earth Science (SES) Program responsive to the needs of an international Global Change Program.

During the course of the week, five high priority research or mission targets were identified to address the interdisciplinary requirements of Earth sciences including geology and geophysics, hydrology, ecology, and climatology. The scope of effort required is very great and substantial domestic interagency and international cooperation will be essential. The new thrusts which emerged at Coolfont are described below and are shown in Table 9-1.

Global Geophysical Network (GGN)

A global network of space geodetic stations capable of millimeter-position accuracy to provide data crucial for both solid Earth sciences and the study of global change was recommended at Coolfont. Although the network would start with the current international/interagency array of Very Long Baseline Interferometry/Satellite Laser Ranging (VLBI/SLR) stations, it would increase by 1995 to include about 200 continuously monitored stations (mainly GPS) at 1000-km spacing around the world. In honor of the pioneering efforts in the field of crustal geodynamics of Dr. Edward A. Flinn, it was suggested this network be called the Fiducial Laboratory for an International Natural Science Network (FLINN). In regions of special study, densely spaced geodetic systems (DSGS) of either permanent arrays or highly mobile systems (GPS and GLRS) would be deployed. The permanent network would provide the global precision tracking for orbit determinations, crucial for gravity model improvement and for missions such as TOPEX/POSEIDON, ERS-1, and EOS. Auxiliary instruments such as superconducting gravimeters and vector magnetometers will use infrastructure provided by the global network.

Such a network is required because, while plate tectonic theory (and NASA Geodynamics) have been spectacularly successful over the past decades in providing a description of global motions at the centimeter-per-year level, it is now necessary to address fundamental questions such as the coupling of the presumed steady motions of plate interiors to the "jerky" motions manifested as earthquakes at plate boundaries, intraplate deformation, mantle rheology and the driving mechanism for plate tectonics, and the relationship of plate tectonics to continental deformation. As such, investigations must go beyond the coarse description provided by rigid plate theory and determine motions on regional scales and at the millimeter-per-year level.

Precise monitoring of positions is required not only to understand the long-term behavior of the solid Earth but also to understand global change on time scales of decades or less. For example, the surface of the solid Earth is undergoing rapid vertical motions (up to 10 mm/yr) in response to Pleistocene deglaciation. These motions lead to changes in volumes of ocean basins and the height of shorelines at rates comparable to those from melting ice

TABLE 9-1. **MISSIONS TO ADDRESS NEW THRUSTS AND ONGOING PROGRAMS**

Large Scale Effort	Missions	SRT Measurement Element	
Core Dynamics	MFE/Magnolia ARISTOTELES	FLINN	geodynamics
Mantle Dynamics	LAGEOS 1,2,3 GP-B	FLINN; DSGS	
Postglacial Rebound & Sea Level Change	Gravity mission ($\dot{g}$)	FLINN	mix of geodynamics & geology
Lithosphere Evolution	EOS ARISTOTELES TOPO* SIR-C SGGM	Airborne campaigns TM/SPOT	
Plate Motion & Deformation	EOS ARISTOTELES TOPO* LAGEOS 1,2,3	FLINN; DSGS Seafloor geodesy; TM/SPOT	
Surface Processes: —soils —transitional areas —volcano/climate interactions	EOS SIR-C TOPO* TIR OVO TOMS	Airborne campaigns; TM/SPOT; FLINN; DSGS	geology

*Topographical mapping mission

and temperature changes in the oceans. Understanding the "signal" of global change in sea level requires understanding the "noise" from the solid Earth. Assessing seismic hazards in regions removed from major plate boundaries, e.g., Armenia, requires regional geodetic coverage in many areas of the globe.

Global Topographic Mapping

Because of the importance of topography to the majority of NASA's Solid Earth Science research objectives, high priorities for the Program are a) to acquire a globally consistent topographic database at moderate resolution, and b) to make available high-resolution topographic data over regional and local areas. Several technological approaches now exist for the space-based acquisition of global topographic data at resolutions of the order of 100 m horizontal and 1 m vertical. However, there is not a clear path for acquisition of intermediate resolution data (30–50 m horizontal, 1 m vertical) in a globally consistent set.

Topographic data are basic to a variety of studies including geologic mapping, the formulation of geophysical models, hydrologic modeling of drainage systems, large scale-ecosystem modeling, and studies of polar ice volume. It is necessary to correct for topographic effects interpreting gravity surveys and it is necessary to know the slope of the land's surface in order to assess the effects of stream erosion, regional drainage, and the hydrologic cycle. Topography is an important element in regional and global geomorphic studies because it reflects the interplay between erosion and the tectonic and volcanic processes of formation. It also plays an important role in pedogenesis and has a strong influence on soil properties such as soil depth, pH, soluble salt content, and potential for erosion or accumulation. Despite the need for these data at suitable scales, they are available for only a few regions of the land's surface. Studies of mountain belts, deserts, tropical rain forests, and polar areas—all critical environments for Earth science research—suffer from inadequate topographic coverage.

The SES Program proposes to establish an interagency working group to develop an implementation plan for the space acquisition of global topographic data that will satisfy a variety of needs. In addition to working with an engineering team on technology-related issues, this group will also address access to existing data which may be limited because of cost or security classification.

Soils and Surface Processes

The land surface (soil, rock, and vegetation cover and geomorphology) has been modified throughout geologic history by climatic and tectonic processes. Today human activity is also changing the Earth's surface, but the anthropogenic impact on the Earth system cannot be assessed without understanding how the factors that cause changes interact with one another over time.

The goals of this research are twofold: a) to understand how the land surface (soil cover and geomorphology) responds to or develops under natural and anthropogenic influences; this understanding can also be used to characterize the paleoclimatic history of regions of interest, and b) to understand how the global land surface is changing on a time scale of months to decades in response to current climatic, tectonic, and human influences.

Global-scale observations of the land surface are required to monitor areas undergoing rapid change from one cover to another (particularly areas of rapid soil degradation, erosion, and redistribution), areas sensitive to change due to natural or anthropogenic pressures (such as margins of arid regions, coastal zones, permafrost regions, areas of glaciation, lacustrine margins), and areas that have a significant influence on global change. Systematic, repetitive measurements of physical and chemical conditions on the Earth's surface at several spatial and temporal scales will be required for these investigations.

It will be necessary to be able to characterize the soil cover of large regions, and remote-sensing techniques must be developed for this purpose. Coordinated field measurements and remote-sensing observations from aircraft and Earth orbit must be key elements of this research program.

The major data requirements are for the combined data sets expected to be available from EOS together with high resolution topography, TM/SPOT data, TIR data. Aircraft campaigns are an important source of data. A major effort to enlarge the number of investigators by creating multidisciplinary teams is expected. Field work involving mapping and dating surficial materials is integral to these studies. Development of a coordinated program of global soils studies will continue at a December 1989 workshop which will include NASA and other federal agencies active in soil studies.

Geopotential Fields

The gravity and magnetic fields of the Earth offer opportunities to study the interior of the Earth—from its lithosphere to the core-mantle boundary. Both fields change with time, and the short wavelength anomalies of these fields identify the structure of the Earth's lithosphere. Our current models of the viscosity structure of the mantle, how it convects, and how it is coupled to the core and lithospheric boundary layers are dependent upon space-based gravity data, in combination with observations of lateral and vertical variability in seismic velocity structure. The long-term variability of the geomagnetic field is related to the dynamics of the Earth and the length of the day. The shorter term variability of the magnetic field is related to the electrical conductivity of the deep mantle. We do not yet accurately know the long-term variability of either of these potential fields.

The shorter wavelength components of the gravity and magnetic fields are poorly known and, with today's technology, can only be measured globally from space by relatively low altitude satellites where the signal is large. Both gravity and magnetic anomalies identify major tectonic features of the lithosphere and dimensions of 100 km or more. The short wavelength magnetic anomalies identify the depth of the Curie isotherm (about 600°C) at which rocks bearing magnetic materials lose their magnetic signature.

Missions already approved, TOPEX/POSEIDON and LAGEOS-2, will provide some additional gravity field information. TOPEX will provide more accurate ocean geoid information, and LAGEOS-2 will enable us to improve our knowledge of the low-degree zonal harmonics and their temporal change. A planned LAGEOS-3 would make some modest additional improvement, but because all three LAGEOS spacecraft will be in high inclinations, additional mini-LAGEOS ($\dot{g}$) spacecraft in low to moderate inclinations are required to do the low degree and order gravity field and its temporal changes. Similarly, in order to determine the main magnetic field and its temporal variations, the Magnetic Field Explorer (MFE)/Magnolia (NASA/CNES) mission is required.

The first chance to demonstrate the feasibility of directly measuring gravity in low-Earth orbit via gradiometry is the European Space Agency (ESA) Earth Probe mission ARISTOTELES. It is proposed that NASA participate in this mission by providing an onboard GPS receiver and the incorporation of magnetometers for measurements of both the crustal field and the main field. The current scenario is for the spacecraft to be placed into a high-altitude orbit by an expendable launch vehicle. During the subsequent 9-month period, the spacecraft will descend to 225 km to undertake the gravity field measurements for about 6 months. The orbit would then be raised to 600–800 km where the mission would continue for another 3 years. The main magnetic field measurement would be obtained during this third phase. If the NASA/ESA ARISTOTELES carries magnetometers, a refinement in resolution to the crustal anomaly maps obtained from Magsat can be achieved. Additionally, if ARISTOTELES has a high-elevation extended mission phase, some main magnetic field modeling improvements can also be made. In any event, ARISTOTELES will provide a very substantial improvement in the gravity field, both in terms of accuracy and resolution and doing so with a homogeneous data set for the first time.

Gravity Probe-B (GP-B) is a mission from the physics community to measure the relativistic Lens-Thirring Effect. Studies have shown that the unique features of the mission, augmented with a GPS receiver and laser cornercube retroreflectors, would make it particularly useful for measurement of the intermediate wavelength gravity field. A quantum increase in the accuracy of the field in terms of gravity will be achieved sometime early next century after the free-flyer flight of the Superconducting Gravity Gradiometer (SGGM). To realize the increase in resolution to meet some of the science requirements, some regions will have to be mapped through the use of aircraft flights.

Volcanic Effects on Climate

That large-scale volcanic eruptions can have observable effects on the Earth's climate is becoming widely recognized in the volcanological community. Essential questions still remain, however, concerning the bounds of these effects in terms of degree, duration, and spatial extent.

In broad terms, it is known that the climatic effects of volcanism are due to the emission of sulfur dioxide (SO_2), because it results in absorption of solar radiation and of aerosols. The study of these effects can be considered in three phases linked to the history of the gases:

- The origin of the SO_2, Cl_2, and F_2, and their abundances as a function of factors such as the type of magma and tectonic setting of the volcano
- The global transportation and residence times of gases and particles injected into the stratosphere, and the reaction of SO_2 to form H_2SO_4
- Modeling of the climate effects of these constituents entailing the measurement of regional temperatures and correlation with volcanic gas dispersal through climate models

The Solid Earth Sciences Program will engage in several observational programs and support scientific investigations to pursue these objectives. Activities will include observation of new eruptions and volcano monitoring using imagery provided by instruments such as the TM, SPOT, TOMS, and AVHRR as well as EOS instruments (MODIS, SAR, ITIR, GLRS, MISR, TES, and HIRIS). It will also develop and install automated field monitoring systems at active volcanoes to observe gaseous emissions, seismicity, and changes in temperature and tilt.

New sensor concepts are proposed in conjunction with this study. The highest priority is an advanced TOMS instrument with improved spectral bands which, while not detracting from ozone measurements, will provide more sensitive and precise SO_2 determinations and may permit the analysis of tropospheric eruption plumes. Also under consideration is the concept of an Orbiting Volcanological Observatory (OVO) designed to measure the abundances of volcanic gases and the level of thermal emissions from active volcanoes. Daily observation and moderate (tens of meters) spatial resolution capability would also make such a system very useful to other disciplines. If studies on the requirements for the gas sensor began in the near future, the system could be ready for launch as an Earth Probe mission some time in the second part of the decade.

Appendices

Appendix A

Earth Science and Applications Division Budget Summaries FY 1985–FY 1990

PROGRAM	FY 1985	FY 1986	FY 1987	FY 1988+ (a)	FY 1988 (b)	FY 1989+ (a)	FY 1989 (b)	FY 1990+
ERBE	8.1	1.9	—	—	—	—	—	—
UARS	55.7	114.0	113.8	95.4	89.2	100.0	85.2	73.9
Scatterometer	12.0	14.0	32.9	22.7	22.6	16.0	10.6	13.8
TOPEX	—	—	18.9	90.0	74.5	98.0	83.0	72.8
Global Geospace Science	—	—	—	25.0	—	102.0	—	—
PAYLOADS								
Solid Earth Observations*	12.1	21.8	21.4	21.1	20.8	25.6	25.3	42.3
Environmental Observations*	7.8	5.3	4.7	4.1	4.1	4.8	6.6	—
Collaborative Solar-Terrestrial (COSTR)	—	—	5.0	15.0	—	44.0	—	—
Tether Payloads	0.9	1.6	5.5	3.4	—	3.7	—	—
OPERATING SATELLITES								
Mission Operations & Data Analysis:								
Earth Science	11.0	16.7	19.5	14.7	14.7	18.5	17.6	24.8
Space Plasma Physics	18.5	18.3	14.1	12.0	—	8.5	—	—
RESEARCH AND ANALYSES								
Upper Atmosphere	31.0	31.1	32.7	34.4	32.7	35.8	31.1	38.1
Oceanic Processs	19.4	17.4	18.0	21.5	20.1	22.2	20.8	24.5
Atmospheric Dynamics/ Radiation	28.5	28.7	31.3	32.9	31.4	34.3	32.0	37.4
Space Plasma Physics	16.7	16.8	20.8	21.5	—	23.0	—	—
Interdisciplinary Research	1.0	1.0	1.1	1.1	1.1	2.2	2.2	2.3
Geodynamics	29.9	21.9	23.2	24.2	23.6	25.3	24.1	38.0
Land Processes	15.6	19.1	19.4	22.6	21.1	23.5	19.9	22.5
EOS	—	—	—	—	—	15.0	14.5	24.2
Airborne Science	—	—	—	—	21.9	—	23.0	19.7
Laser Network Operations	—	8.1	8.4	8.9	8.8	9.4	8.8	9.6
TOTAL (Dollars In Millions)	268.2	335.8	390.7	470.5	386.6	611.8	407.7	443.9
ESTIMATED REIMBURSABLE SATELLITE DEVELOPMENT FUNDS								
NOAA	95.0	65.0	50.0	25.0		90.0		43.0
GOES	95.0	145.0	115.0	120.0		210.0		164.0
TOTAL (Dollars In Millions)	190.0	210.0	165.0	145.0		300.0		207.0

\+ Presidential Request
(a) Prior to the reorganization of the Earth Science and Application Division, October 1987, and prior to Appropriation Realignment.
(b) Post-reorganization of the Division, and post-Appropriation Realignment.
* Begining in FY 1990, Solid Earth Observations and Environmental Observations have been combined as a single line item, "Earth Science."

Appendix B

Manned Observations of Earth from Space

Since 1962, some 85,000 photographs of the Earth as seen from space have been taken by astronauts on board manned spacecraft. From the early days of the Mercury program through the Gemini, Apollo, Apollo-Soyuz, Skylab, and the Space Shuttle programs, a spectacular collection of images of the features of the Earth has been amassed. The length-of-record and the geographic distribution of these space photographs provide a rich source of data for the study of all aspects of Earth science, and particularly for the investigation of large-scale environmental change.

Low Earth Orbit (LEO) offers a unique perspective at an altitude between those of research aircraft and remote satellites, resulting in levels of details and areas of coverage unobtainable from other platforms. The use of orbital photography, often preselected by scientists themselves, is an economical and complementary data source for researchers. While analog space photography does not compete with the torrent of digital imagery made available since Landsat-1, color photos created by an individual in space of the weather systems, oceans, and the land masses of our planet Earth have a deeper meaning for human beings than does a black-and-white digital image from a meteorological satellite. One of the most famous pictures from space is the Apollo-8 view, taken at Christmas 1968, of the Earth rising above the bleak surface of the Moon, and seen on the back cover of this report. Such pictures enable the beauty of our home planet to be easily documented and communicated to millions of people around the world. On a scientific level, space photography has led to the discovery of many unknown or hypothesized phenomena, and has continually demonstrated that, quickly and effectively, a trained observer in orbit can react to and record the unusual and the unknown.

At the NASA-Johnson Space Center Space Shuttle Earth Observations Office (SSEOO), a primary mission is to train Shuttle astronauts to gather systematic and scientifically meaningful observations of Earth during their missions. The office also coordinates and ranks requests from NASA and the science community for specific Earth images. Another basic function is the archiving, cataloging, and indexing of space photography as both printed and electronic data bases. Many of the catalogs of pre-Shuttle missions are now out-of-print, but the data have been incorporated into SSEOO's master electronic data base. A printed composite catalog of photographs from the first 24 Shuttle missions is now being published (1989 Composite Catalog of Earth Photography) and electronic versions have been distributed to designated public archives. Prints, negatives, slides, and video disks of U.S. astronaut pictures are available from a number of sources at reasonable cost, and computer searches can be run to identify photographs of particular interest. (See details in Sources section). The introduction of a standardized electronic index has enhanced the usefulness of these data, and the evolution of mini-computer, and now microcomputer, hardware and software permit desktop image processing from both analog and digital sources.

NASA ASTRONAUT SPACE PHOTOGRAPHY

Program/Mission	Date	Photos
Mercury	1961–63	400
Gemini	1965–66	2,520
Apollo	1968–72	2,138
Skylab	1973–74	40,767
Apollo-Soyuz	1975	751
Space Shuttle	1981–86	38,176
TOTAL		**84,752***

*About 10% of these document mission activities; the rest are Earth observations.

Shuttle missions (usually from 3 to 7 days duration) normally carry about 1,600 frames of 70 mm film for the NASA-modified Hasselblad EL/M camera, together with 50, 100, and 250 mm lenses. Most film is now color visible (Kodak 5017 Ektachrome 64 professional), although higher speed film, black and white, and color infrared (CIR) have been used. The first Space Shuttle use of CIR film was during the STS-41G mission, October 5–13, 1984, a mission that was dedicated to Earth science, and that carried the SIR-B, MAPS, and FILE experiments.

SSEOO is evaluating many suggestions for improving space photography techniques, including the use of negative color film, Kodachrome and non-Kodak films, a pointable camera system in the cargo bay, the retrofit of more transparent orbiter windows, and electronic imaging systems. Procedures are also being developed for digitizing handheld photographs for incorporation into Geographic Information Systems (GIS). Space Shuttle onboard photography tests will continue and will serve as stepping stones towards Earth science operations aboard the permanently manned Space Station Freedom around the turn of the century.

HASSELBLAD PHOTOGRAPHY CHARACTERISTICS

Lens (mm) Nadir	FOV (km)	Spatial Resol. (m)
50	330 × 330	150
100	165 × 165	80
250	65 × 65	30

A new camera system—the Aero-Technica Linhof camera with advanced optics, vacuum-plate film platen, clock, and 4 x 5 inch film format—has been used on some Shuttle missions and has provided outstanding Earth photography.

Astronaut handheld photography is analog data that can be analyzed in either an analog or digitized manner. Shuttle pictures can be used as wide-field aerial photographs, or once digitized, be subjected to standard image processing techniques of rectification, overlaying, and GIS input, classification, mensuration, enhancement, multitemporal and multisource comparisons, etc. Digitized images show levels of precision in measuring areal change that are equivalent to those of Landsat TM images and Large Format Camera (LFC) photography. However, the cost of data, prior to processing, is much lower than prints from Landsat TM or from SPOT. Less time and equipment is needed to interpret space photography, so it can be a very useful tool, for example, for teaching.

Geologists were among the first to recognize the importance of viewing Earth from space, because many landforms are too large to be photographed from the air. Space pictures provide valuable true-color depiction of many significant areas and phenomena, with a wide variety of solar illumination and look angles. Landsat and SPOT provide black-and-white or false color images which while excellent for distinguishing water and vegetation, add little to the interpretation of geologic materials unless specially processed. Ground coverage and resolution nearly identical to Landsat MSS and TM sensors can be achieved.

Astronaut photography offers unique opportunities, because of the flexibility and training of the on-orbit observer, to document dynamic activity such as dust storms, volcanoes, and the like. For example, astronauts have photographed more than 36 volcanic eruption plumes, some of which would not have been reported otherwise. In addition, the stereographic capability of astronaut photography permits three-dimensional interpretation of geologic landforms, which is useful in the analysis of structural geology. Astronauts have also photographed about 20 known impact craters as part of a project to discover presently unknown craters in Africa, South America, and Australia.

Tremendous flexibility arises from the fact that lenses on the Hasselblad cameras can be changed easily to achieve appropriate coverage of a particular scene. An erupting volcano can be shot with a 250 mm lens to provide the best spatial resolution of advancing lava flows, while a 50 mm lens enables an entire mountain system to be captured within a single frame.

Global tropical areas have been a natural subject of photographic coverage both from the Space Shuttle missions and earlier manned spaceflight programs. The almost 30-year history of the programs has enabled remote sensing time series to be compiled for unique observations of environmental change in a number of areas. Because the effective coverage of Shuttle flights is 30°North to 30°South, environmental monitoring of global tropics—the least well-documented, least-understood, yet potentially crucial areas in terms of the global environment—can be achieved. The Amazon Basin has been an area of intense study. Gemini photography in the mid-1960s and Skylab pictures from 1973–1974 showed the Amazon Basin and the western Serras as largely covered with closed-canopy forests at that time. However, beginning in 1982, pictures taken from the Space Shuttle showed large cleared areas and hydrological changes in Bolivia and Brazil that were not visible otherwise. Using such photographs, it is now possible to study deforestation, soil erosion, supersedimentation in streams, lake and estuarine environments, and desertification, in areas such as the Greater Amazon, tropical Africa and Madagascar, South and Southeastern Asia, and the Indo-Pacifica archipelagoes. For example, deforestation and consequent soil erosion in Madagascar has been clearly documented by repetitive astronaut photography. The falling water levels of Lake Chad have been similarly documented. (See photograph).

Applications in meteorology are widespread. Spectacular views of the Earth's weather systems taken from Gemini, Apollo, Skylab, and the Shuttle have appeared extensively in publications ranging from textbooks to magazines and in high-resolution imagery studies. Astronaut pictures enable cloud and surface phenomena to be viewed from a wide variety of angles and oblique perspectives, with shadowing and lighting giving emphasis to the vertical dimensions of cloud patterns not clearly evident in near-nadir imagery available from operational satellites.

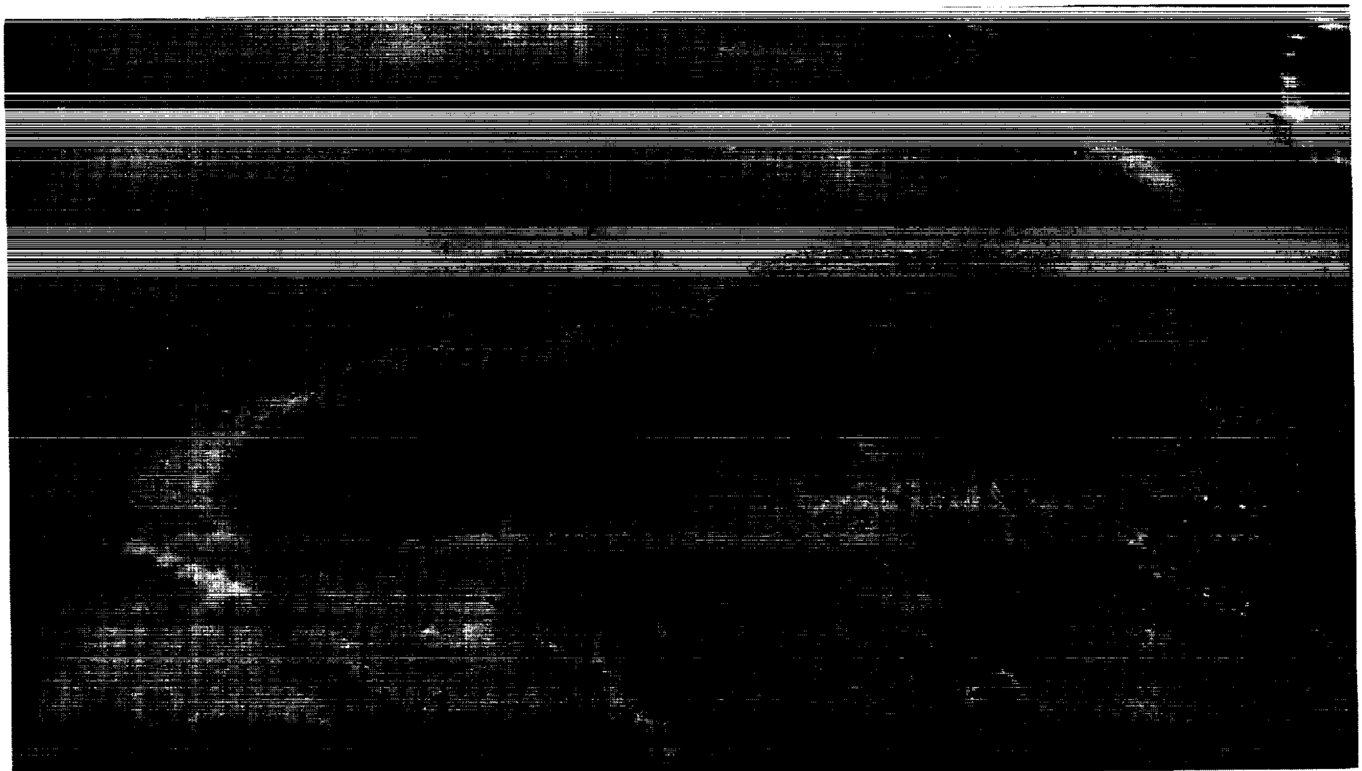
Sources

A full description of astronaut photography over the years can be found in the March 1989 issue (Vol 4, No.1) of the journal *Geocarto International*, (Geocarto International Centre, GPO Box 4122, Hong Kong: ISSN 1010-6049), which is entirely devoted to an in-depth discussion of the history of space photography. In June 1989, the journal initiated a new column covering individual Shuttle missions with an extensive description of Earth observations taken during Discovery's Mission to Earth (STS-26, September 29–October 3, 1988).

Dr. Michael Helfert heads the Space Shuttle Earth Observations Office (SSEOO) at NASA-Johnson Space Center, telephone (713) 483-5333. As its name implies, SSEOO focuses on Shuttle photography, and its printed composite catalog of Shuttle photography (SSEOO, 1989 Composite Catalog of Earth Photography) is now being published. However, SSEOO's electronic data base, which is available in a number of public archives, includes all U.S. space photography of the Earth, not just Shuttle pictures. One of the main repositories of this master data base is the User Services Section, EROS Data Center (EDC), Sioux Falls, South Dakota, 57198, U.S.A., telephone (605) 594-6151. The EDC also has copies of SSEOO mission catalogs and can perform data base searches using more than 15 variables.

The Air and Space Museum of the Smithsonian Institution (telephone [202] 357-3133), and the Library of Congress ([202] 707-6500) in Washington D.C.,

THE DRYING UP OF LAKE CHAD, NORTH EAST AFRICA



Lake Chad, in northeast Africa, was photographed during STS-26 at its lowest level ever seen by astronauts. The current surface area of the lake is apparent at the southern end of the former lake basin (on the right) with the lighter water surface distinguished from the darker area of the basin. The surface area of the lake has decreased by a reported 90% in the last twenty years.

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

and the Technology Applications Center of the University of New Mexico, Albuquerque, New Mexico, (telephone [505] 277-3622) also have copies of these films. The Smithsonian has black-and-white and some color prints available, and has issued a video disk (Archival Disk #5), which contains all the Hasselblad Earth photography from Space Shuttle missions 1–24, for public sale. The video disk costs $55 plus postage and is available from the Smithsonian Institute Press, Department 900, Blue Ridge Summit, PA 17294, telephone (717) 794-2148.

Additional viewing sources (microfilm only) in the United States are the 14 National Cartographic Information centers (NCIC). In addition, a browse facility of Shuttle photography is offered at the Lunar Planetary Institute, telephone (713) 486-2139, immediately adjacent to the NASA-Johnson Space Center in Houston. Pictures can also be ordered from Media Services at the NASA-Johnson Space Center, telephone (713) 483-4231.

EARTH PHOTOGRAPHY ON SPACE SHUTTLE MISSIONS

Mission	Dates	Inclination/ Altitude (nm)	Photos
STS-1	4/81	40°/145	475
STS-2	11/81	38°/140	842
STS-3	3/82	38°/128	514
STS-4	6/82	28.4°/172	459
STS-5	11/82	28.4°/160	833
STS-6	4/83	28.4°/150	658
STS-7	6/83	28.4°/170	904
STS-8	8/83	28.4°/120-166	2028
STS- 9 (41-A)	11/83	57°/135	2239
STS-11 (41-B)	2/84	28.4°/176	1693
STS-13 (41-C)	4/84	28.4°/272	1630
STS-14 (41-D)	8/84	28.4°/179	1648
STS-17 (41-G)	10/84	57°/120-190	2476
STS-19 (51-A)	11/84	28.4°/195	2055
STS-20 (51-C)	1/85	28.4°/190	1095
STS-23 (51-D)	4/85	28.4°/251	1469
STS-21 (51-B)	4/85	57°/193	2392
STS-25 (51-G)	6/85	28.4°/209	1868
STS-24 (51-F)	7/85	49.5°/173	1554
STS-27 (51-I)	8/85	28.4°/242	1830
STS-28 (51-J)	10/85	28.4°/278	1104
STS-29 (61-A)	10/85	57°/180	3534
STS-30 (61-B)	11/85	28.4°/209	2737
STS-32 (61-C)	1/86	28.4°/175	2148
TOTAL			38,176

nm = nautical miles

Appendix C

Acronyms and Abbreviations

ABLE	Atmospheric Boundary Layer Experiment
ACRIM	Active Cavity Radiometer Irradiance Monitor (EOS)
ADEOS	Advanced Earth Observing Satellite (Japan)
AIRS	Atmospheric Infrared Sounder (EOS)
AFGL	Air Force Geophysics Laboratory
ALT	Altimeter
ALT-2	Altimeter (ESA)
AMMS	Advanced Microwave Moisture Sensor
AMPR	Advanced Microwave Precipitation Radiometer
AMRIR	Advanced Medium Resolution Imaging Radiometer
AMSR	Advanced Microwave Scanning Radiometer (Japan)
AMSU	Advanced Microwave Sounding Unit (EOS)
AO	Announcement of Opportunity
AOS	Archive and Operations System
ASAS	Advanced Solid State Array Spectrometer
ASTEX	Atlantic Stratocumulus Transition Experiment
ATLAS	Atmospheric Laboratory for Applications and Science
ATLID	Atmospheric Lidar (ESA)
ATMOS	Atmospheric Trace Molecules Observed by Spectroscopy
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible Infrared Imaging Spectrometer
CAWG	Calibration Advisory Working Group
CDA	Command and Data Acquisition System
CDHF	Central Data-Handling Facility
CDOS	Customer Data and Operations System
CDP	Crustal Dynamics Project
CEOS	Committee on Earth Observing Satellites
CERES	Clouds and the Earth's Radiant Energy System (EOS)
CES	Committee on Earth Sciences
CFC	Chlorofluorocarbon
CISD	Communications and Information Systems Division
CITE	Chemical Instrumentation Test and Evaluation
CLS	Cloud Lidar System
CMA	Chemical Manufacturers' Association
CNES	French National Center for Space Studies (Centre National d'Etudes Spatiales)
CNR	National Research Council of Italy (Consiglio Nazionale delle Recerche)
COARE	Coupled Oceans Atmospheric Responses Experiment
CRRES	Combined Release and Radiation Effects Satellite
CS	Color Scanner
CTS	Cloud Top Scanner
CZCS	Coastal Zone Color Scanner
DADS	Data Archive and Distribution System
DCS	Data Collection System
DE	Dynamics Explorer
DHS	Data Handling System
DIAL	Differential Absorption Lidar
DIF	Data Interface Facility
DMSP	Defense Meteorological Satellite Program
DLS	Dynamic Limb Sounder (EOS)
DoD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DSGS	Densely Spaced Geodetic Systems
EMOC	EOS Mission Operations Center
ENACEOS	Energetic Neutral Atom Camera for EOS
ESGP	Earth Science Geostationary Platform
EOS	Earth Observing System
EOSAT	Earth Observation Satellite Co.

EOSDIS	EOS Data and Information System
EOSP	Earth Observing Scanning Polarimeter
EPA	Environmental Protection Agency
EPOP	European Polar Orbiting Platform
ERB	Earth Radiation Budget Instrument
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite
EROS	Earth Resources Observation System
ERS-1	Earth Remote Sensing Satellite (ESA)
ESA	European Space Agency
ESAD	Earth Science and Applications Division
ESADS	Earth Science and Applications Data System
ESMR	Electrically Scanning Microwave Radiometer
ESN	Earth Science Net
ESSC	Earth System Sciences Committee
ETO	Extensive Time Observations
EUMETSAT	European Meteorological Satellite Organization
FAA	Federal Aviation Administration
FASINEX	Frontal Air-Sea Interaction Experiment
FCCSET	Federal Coordinating Council for Science, Engineering, and Technology
FDF	Flight Dynamics Facility
FIFE	First ISLSCP Field Experiment
FIRE	First ISCCP Regional Experiment
FLINN	Fiducial Laboratory for an International Science Network
GARP	Global Atmospheric Research Program
GEMS	Global Environment Monitoring System
GEO	Geosynchronous Earth Orbit
GEOS	Geodynamics Experimental Ocean Satellite
Geosat	Navy Geodetic Satellite
GFFC	Geophysical Fluid Flow Cell
GGI	GPS Geoscience Instrument (EOS)
GGM	Gravity Gradiometer Mission
GGN	Global Geophysical Network
GGS	Global Geospace Science Program
GISS	Goddard Institute for Space Studies
GLOBE	Global Backscatter Experiment
GLRS	Geoscience Laser Ranging System
GCM	General Circulation Model
GOES	Geostationary Operational Environmental Satellite
GOFS	Global Ocean Flux Study
GOLD	Global On-Line Data
GOMR	Global Ozone Monitoring Radiometer
GOS	Geomagnetic Observing System (EOS)
GP-B	Gravity Probe-B
GPS	Global Positioning Satellite System
GRADIO	French Gravity Gradiometer
GRID	Global Resources Information Database
GRIS	Global Resources Information System
GRM	Geopotential Research Mission
GSFC	Goddard Space Flight Center
GTCP	Global Tropospheric Chemistry Program
GTE	Global Tropospheric Experiment
GTO	Geosynchronous Transfer Orbit
HALOE	Halogen Occultation Experiment
HAPEX	Hydrological Atmospheric Pilot Experiment
HCMM	Heat Capacity Mapping Mission
HIMSS	High Resolution Microwave Spectrometer Sounder (EOS)
HIRIS	High Resolution Imaging Spectrometer (EOS)
HIRRLS	High Resolution Research Limb Sounder (EOS)
HIRS	High Resolution Infrared Sounder
HIS	High Resolution Interferometer Sounder
HMMR	High Resolution Multifrequency Microwave Radiometer
HRDI	High Resolution Doppler Interferometer
HRIS	High Resolution Imaging Spectrometer (ESA)
IAU	International Astronomical Union
ICC	Instrument Control Center (EOS)
ICSU	International Council of Scientific Unions
ICWG	International Coordination Working Group

IERS	International Earth Rotation Service
IFO	Intensive Field Observations
IGBP	International Geosphere-Biosphere Program
IICF	Interdisciplinary Investigator Computing Facilities
IMC	Information Management Center
IML	International Microgravity Laboratory
INSAT	Indian National Satellite
IPAR	Intercepted Photosynthetically Active Radiation
IPEI	Ionospheric Plasma and Electrodynamics Instrument (EOS)
IPOMS	International Polar-Orbiting Meteorological Satellite
IR	Infrared
IRAP	ISLSCP Retrospective Analysis Program
IRIS	Italian Research Interim Stage
IRM	Ion Release Module (Germany)
ISAMS	Improved Stratospheric and Mesospheric Sounder (United Kingdom)
ISAS	Institute of Space and Astronautical Sciences (Japan)
ISCCP	International Satellite Cloud Climatology Project
ISEE	International Sun-Earth Explorer
ISLSCP	International Satellite Land Surface Climatology Project
ISO	Information Systems Office
IST	Instrument Support Terminal
ISY	International Space Year
ITIR	Intermediate and Thermal Infrared Radiometer (Japan)
IWG	Investigator Working Group
IUGG	International Union of Geodesy and Geophysics
IUGS	International Union of Geophysical Sciences
IWGDMGC	Interagency Working Group on Data Management for Global Change
JERS-1	Japan's Earth Resources Satellite
JOI	Joint Oceanographic Institutions Inc.
JPL	Jet Propulsion Laboratory
JPOP	Japanese Polar Orbiting Platform
LAGEOS	Laser Geodynamics Satellite
Landsat	Land Remote Sensing Satellite
LASA	LIDAR Atmospheric Sounder and Altimeter
LASE	Laser Atmospheric Sensing Experiment
LAWS	Laser Atmospheric Wind Sounder (EOS)
LBPMR	L-Band Pushbroom Microwave Radiometer
LEO	Low Earth Orbit
LFC	Large Format Camera
LIDAR	Light Detection and Ranging
LIMS	Limb Infrared Monitor of the Stratosphere
LIS	Lightning Imaging Sensor (EOS)
LMS	Lightning Mapper Sensor
LTER	Long Term Ecological Research Site
Magsat	Magnetic Field Satellite
MAMS	Multispectral Atmospheric Mapping Sensor
MAPS	Measurement of Air Pollution from Satellites
McIDAS	Man-Computer Interactive Data Access System
MCR	Microwave Cloud Radiometer
MERI	Moderate Resolution Imaging Spectrometer (ESA)
METSAT	Meteorological Satellite
MFE	Magnetic Field Explorer
MIDDS	Meteorological Interactive Data Display System
MISR	Multi-angle Imaging Spectro-Radiometer (EOS)
MLS	Microwave Limb Sounder (EOS)
MMOC	Multimission Operations Center
MMS	Multimission Modular Spacecraft
MOCS	Multichannel Ocean Color Scanner
MODIS	Moderate Resolution Imaging Spectrometer (EOS)
MOPITT	Measurements of Pollution in the Troposphere (EOS)
MOS	Marine Observation Satellite
MOU	Memorandum of Understanding
MPR	Microwave Precipitation Sounder

MR	Microwave Radiometer
MSS	Multispectral Scanner
MSU	Microwave Sounding Unit
MTE	Mesosphere-Thermosphere Explorer
MTPE	Mission to Planet Earth
MTS	Microwave Temperature Sounder
NAC	NASA Advisory Committee
NAR	Non-Advocacy Review
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications Network
NASDA	National Space Development Agency (Japan)
NCAR	National Center for Atmospheric Research
NCC	Network Control Center (EOS)
NDSC	Network for the Detection of Stratospheric Change
NEMS	Navigation and Environmental Monitoring System
NEOS	National Earth Orientation Service
NERC	National Environmental Research Centre (United Kingdom)
NESDIS	National Environmental Satellite, Data, and Information Service
NMC	National Meteorology Center
NMD	NASA Master Directory
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanography Data Center
NODS	NASA Ocean Data System
NOSS	National Oceanic Satellite System
NPOP	NASA Polar Orbiting Platform
NPSS	NASA Packet Switched System
NRA	NASA Research Announcement
NRC	National Research Council
NSCAT	NASA Scatterometer
NSF	National Science Foundation
NSI	NASA Science Internet
NSN	NASA Science Network
NSSDC	National Space Science Data Center
NSTL	National Space Technology Laboratories
NWP	Numerical Weather Prediction
OCI	Ocean Color Imager
OCS	Ocean Color Scanner
OCTS	Ocean Color and Temperature Sensor
ODAS	Oceanographic Data Acquisition System
OHC	Observatoire de Haute Provence
OMB	Office of Management and Budget
ONR	Office of Naval Research
OSIP	Operational Satellite Improvement Program
OSSA	Office of Space Science and Applications
OTSR	Optimum Track Ship Routing
OVO	Orbiting Volcanological Observatory
PDMP	Project Data Management Plan
PEM	Pacific Exploratory Mission
PICF	Principal Investigator Computing Facilities
PIDAS	Portable Instant Display and Analysis Spectrometer
PLDS	Pilot Land Data System
POEMS	POsitron Electron Magnet Spectrometer (EOS)
POES	Polar-Orbiting Operational Environmental Satellite
PROMIS	Polar Region and Outer Magnetosphere International Study
PSC	Platform Support Center (EOS)
PSCs	Polar Stratospheric Clouds
PSCN	Program Support Communications Network
PSN	Piano Spaziale Nationale (Italy)
Radarsat	Radar Satellite (Canada)
RGS	Receiving Ground Station
ROCOZ	Rocket Ozone Correlation Program
ROWS	Radar Ocean Wave Spectrometer
S&R	Search & Rescue System
SAFIRE	Spectroscopy of the Atmosphere using Far Infrared Emission
SAGE	Stratospheric Aerosol and Gas Experiment
SAIS	Science and Applications Information System
SAM II	Stratospheric Aerosol Measurement II

SAMS	Stratospheric and Mesospheric Sounder
SAR	Synthetic Aperture Radar
SBUV	Solar Backscatter Ultraviolet Spectrometer
SCANSCAT	Advanced Scatterometer for Studies in Meteorology and Oceanography (EOS)
SCATT-2	Wind Scatterometer (ESA)
SCR	Surface Contouring Radar
Seasat	Sea Satellite
SEM	Space Environment Monitor
SES	Solid Earth Science
SGG	Supercooled Gravity Gradiometer
SGGE	Supercooled Gravity Gradiometer Experiment
SGGM	Supercooled Gravity Gradiometer Mission
SIR	Spaceborne Imaging Radar
SLR	Satellite Laser Ranging
SME	Solar Mesosphere Explorer
SMM	Solar Maximum Mission
SMMR	Scanning Multispectral Microwave Radiometer
SOLSTICE	Solar Stellar Irradiance Comparison Experiment (EOS)
SPOT	Satellite pour l'Observation de la Terre (France)
SRB	Surface Radiation Budget
SRL	Shuttle Radar Lab
SSBUV	Shuttle Solar Backscatter Ultraviolet Spectrometer
SSIS	Space Station Information System
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
SSU	Stratospheric Sounding Unit
STA	Science and Technology Agency (Japan)
STOIC	Stratospheric Ozone Intercomparison Campaign
STORM	Storm Scale Operational and Research Meteorology
STP	Space Test Program
SUSIM	Solar Ultraviolet Spectral Irradiance Monitor
SVI	Spectral Vegetation Index
SWADE	Surface Wave Dynamics Experiment
SWIRLS	Stratospheric Wind Infrared Limb Sounder (EOS)
TDRSS	Tracking and Data Relay Satellite System
TEA	Transverse Excited Atmospheric Pressure Laser
TES	Tropospheric Emission Spectrometer (EOS)
THEP	TOGA Heat Exchange Program
TIGER	Thermal Infrared Ground Emission Radiometer (EOS)
TIMS	Thermal Infrared Multispectral Scanner
TIR	Thermal Infrared
TIROS	Television Infrared Observing Satellite
TM	Thematic Mapper
TMCF	Team Member Computing Facilities
TMO	Table Mountain Observatory
TMS	Thematic Mapper Simulator
TOGA	Tropical Ocean Global Atmosphere Program
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TRACE	TRansport and Chemistry near the Equator Program
TRACER	Tropospheric Radiometer for Atmospheric Chemistry and Environmental Research (EOS)
TRMM	Tropical Rainfall Measuring Mission
TSS	Tethered Satellite System
TSWG	Topography Science Working Group
TWT	Traveling Wave Tube
UN	United Nations
UARP	Upper Atmosphere Research Program
UARS	Upper Atmosphere Research Satellite
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UNIDATA	University Data Broadcast Project
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VAS	VISSR Atmospheric Sounder
VISSR	Visible and Infrared Spin-Scan Radiometer

VLBI	Very Long Baseline Interferometry
WCRP	World Climate Research Program
WEFAX	Weather Facsimile
WEGENER	Working Group of European Geoscientists for the Establishment of Networks for Earthquake Research
WFF	Wallops Flight Facility
WINDII	Wind Imaging Interferometer (Canada)
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WP-3	Work Package 3
XIE	X-Ray Imaging Equipment (EOS)

Appendix D

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