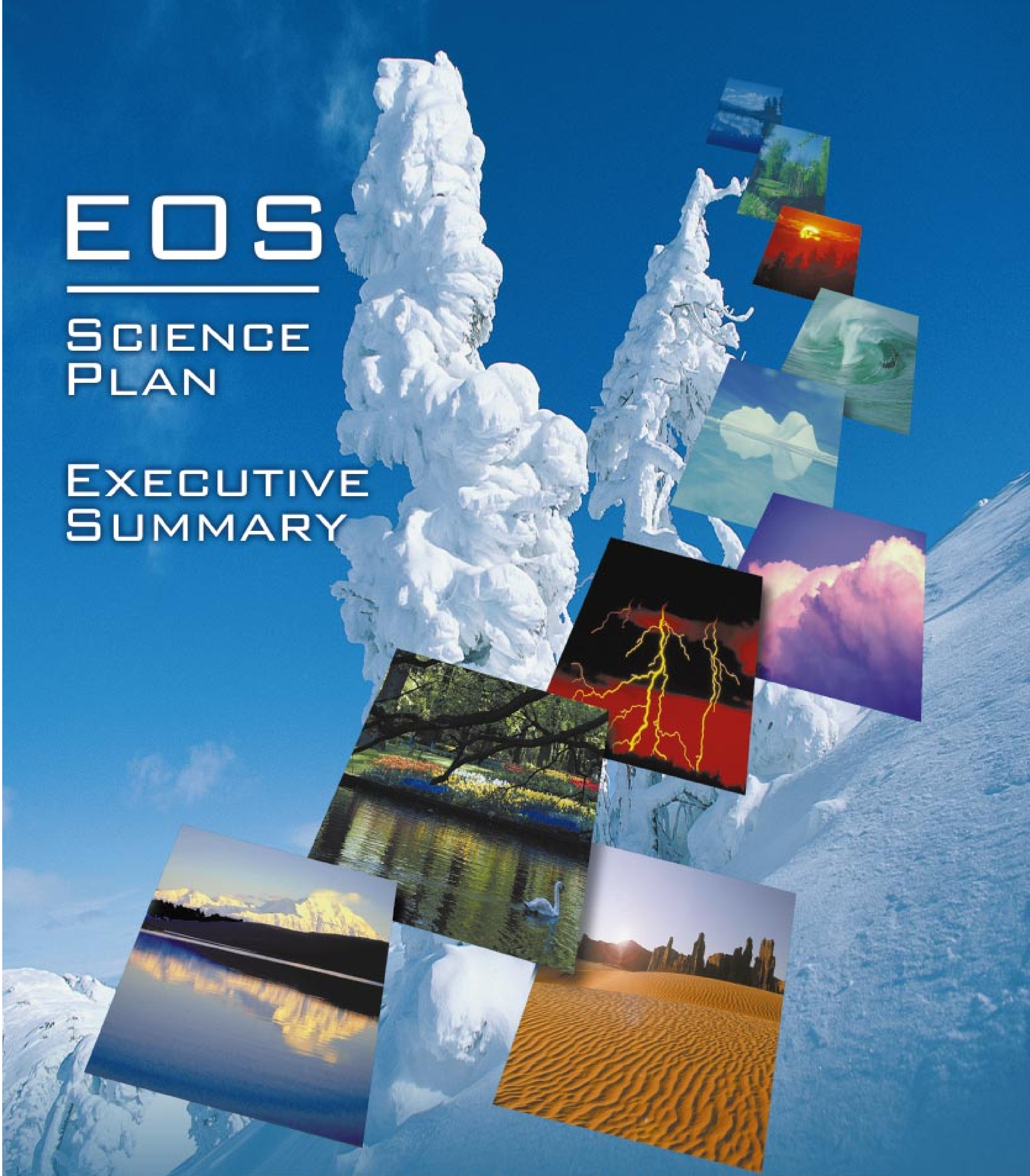
EOS

Science Plan

Executive Summary



The State of Science in the EOS Program

EOS

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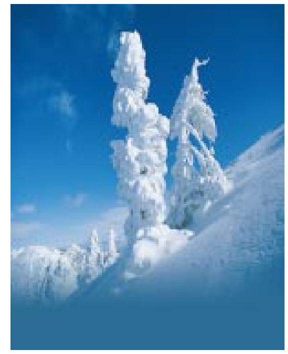

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Foreword

From the dawn of space exploration NASA has been in the forefront of providing the unique vantage point of space as an ideal setting for observing Earth as a whole system consisting of atmosphere, oceans, and continents capable of supporting life in our solar system. Today, NASA continues to sponsor research and development towards understanding the origins of life in the universe. The best proxy for this search and discover mission is life on Earth, and the NASA Earth Science Enterprise captures the spirit of exploration and focuses it back on our home planet. But this requires understanding Earth as an integrated system of atmosphere, land, oceans, and life, which has evolved in the past and will continue to evolve in the future. Building on our observations of the Earth since the earliest days of the space program—NASA built the first weather and land observing satellites—we are using orbiting spacecraft to bring congruency to multiple disciplines within Earth sciences through integrated observations, interdisciplinary scientific research and analysis, and modeling. This is the blueprint for the Earth Science Enterprise at NASA and its Earth Observing System (EOS) program.

The EOS program was established in 1991 as a U.S. Presidential initiative to provide in-depth scientific understanding about the functioning of Earth as a system. It was envisioned that such scientific knowledge would provide the foundation for understanding the natural and human-induced variations in Earth's climate system and also provide a sound basis for environmental policy decision making. Beyond scientific discovery and explorations, it was also envisioned that EOS would have practical societal benefits in the form of providing scientific knowledge toward the efficient production of food and fiber, management of fresh water resources, and improvement of air quality. Less than a decade later, EOS is now a reality and delivering on its promises. During the first phase of the EOS program NASA is funding the development and launch of 25 satellites, and a uniquely comprehensive Earth observations-related data and information system. Hundreds of Earth scientists and engineers are supported, and more than 350 students per year are pursuing graduate degrees in Earth science with NASA funding.

The EOS Science Plan is the product of several years of discussion and debate among the EOS investigators. The considerable time required to develop this document should be viewed as a major strength because of the deep-rooted commitments of the contributors to this document and their ability to deliver on their promise. The objective of this Plan is to convey how EOS investigators plan to utilize the space-based and in situ observations along with modeling and data analysis methods/techniques to address the EOS scientific and applications objectives. Therefore, the principal intended audience for this plan is the body of international Earth scientists and science program directors. Given the complexity of the task at hand and the level of details that had to be provided, the Pan became more than 350 pages long. A short version of the Plan has also been developed in the form of an Executive Summary. We believe that these two documents will be seen to be an effective means of communicating the scientific priorities of the EOS program and how NASA and EOS investigators plan to implement these priorities during the next 5-7 years.

As we move towards the next century the changing Earth's environment will be the focus of many agricultural, industrial, and societal concerns and policy decisions. NASA's Earth Science Enterprise is committed to timely provision of the scientific knowledge needed by world leaders to formulate sound and equitable environmental decisions.

Ghassem R. Asrar
Associate Administrator

Office of Earth Science
NASA Headquarters
Washington, D.C.

Special Note about the Summary

The EOS Science Plan is a lengthy document that describes in great detail the state of the science being investigated by participants in NASA's Earth Observing System (EOS). This Executive Summary has been prepared as a companion document that summarizes all of the elements of the full Science Plan, but sacrifices the degree of detail that appears in the full document. Both in this companion document and in the full document, readers will find presentations on the nature of the EOS Program and the background of concerns and recommendations that led to its formation.

This Executive Summary contains an overview chapter provided by E. J. Barron and then seven topical science chapters as follows:

2. Radiation, clouds, water vapor, precipitation, and atmospheric circulation
   D. L. Hartmann – University of Washington

3. Ocean circulation, productivity, and exchange with the atmosphere
   D. A. Rothrock – University of Washington

4. Atmospheric chemistry and greenhouse gases
   D. Schimel – National Center for Atmospheric Research

5. Land ecosystems and hydrology
   S. W. Running – University of Montana
   G. J. Collatz – Goddard Space Flight Center
   J. Washburne – University of Arizona
   S. Sorooshian – University of Arizona

6. Cryospheric systems
   B. E. Goodison – Atmospheric Environment Service, Canada
   R. D. Brown – Atmospheric Environment Service, Canada
   R. G. Crane – The Pennsylvania State University

7. Ozone and stratospheric chemistry
   M. R. Schoeberl – Goddard Space Flight Center

8. Volcanoes and climate effects of aerosol
   D. L. Hartmann – University of Washington
   P. Mouginis-Mark – University of Hawaii

Readers wishing more details about the IDS investigations or the planned EOS spacecraft missions and the instruments they will carry are advised to consult the 1999 edition of the Earth Science Enterprise/EOS Reference Handbook. The handbook also provides the names of all IDS principal investigators and co-investigators as well as the names of the EOS instrument team leaders, team members, principal investigators, and co-investigators. An excellent way to keep current with EOS developments is to consult the EOS Project Science Office website at http://eos.nasa.gov/.

It should be noted that EOS is a fluid program, with changes in long-term plans always a possibility due to new scientific developments or to budgetary considerations. Authors and editors have tried to keep abreast of changes in mission and instrument names, but some of the older terminology may not have been caught in every instance. For this we apologize.

Acknowledgments

Special thanks go to D. A. Rothrock, University of Washington, who provided the outline for all the topical science chapters, and thus, in a sense, gave the necessary impetus to the launching of this plan. Much of the technical material in the plan was provided not only by the listed lead authors and named contributors, but also by many other unnamed EOS scientists and engineers. R. Greenstone and W. R. Bandeen (both of Raytheon Corporation) provided technical editing throughout the lengthy process of assembling and refining in standard format the text and appendices of this plan. Design and layout of the plan were the work of Sterling Spangler (also of Raytheon Corporation).

-Michael D. King
EOS Senior Project Scientist

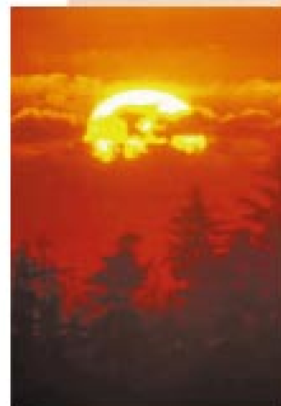
January 1999

Chapter 1

EOS Science Plan Overview

Introduction

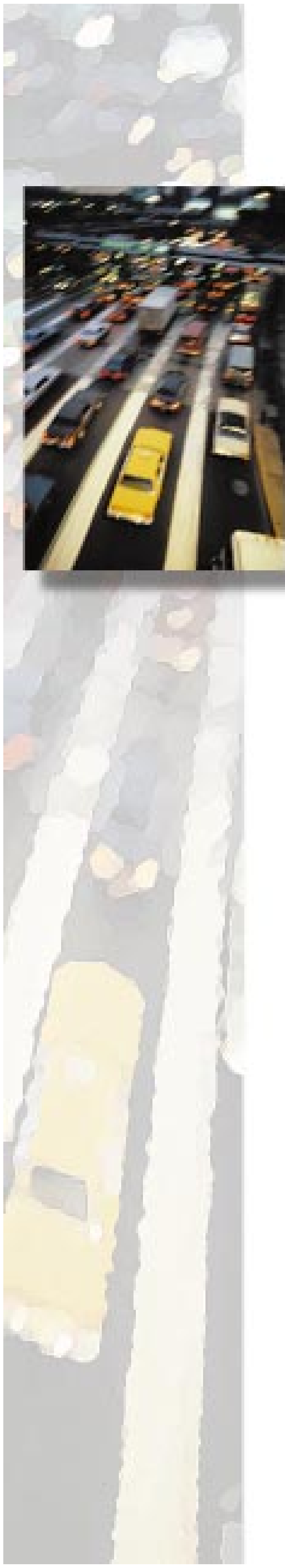
Chapter 1, as its name implies, gives an overview of the seven topical science chapters that follow. In addition, it provides some of the background that has led up to the establishment of NASA's Earth Observing System. In succeeding sections EOS support to various field campaigns is presented, and the measurement strategy that has been adopted for EOS is explained. The chapter ends with a presentation on EOS contributions to national goals and needs related to global change and a summary that brings out the critical role of EOS in addressing the key challenge to develop the capability to predict the changes that will occur in the next decade to century, both naturally and in response to human activity.



Impetus for EOS

The development of EOS can be traced back to 1979 and the establishment of the World Climate Research Program, which was an international effort to understand the physical basis of climate in response to droughts and floods that revealed societal vulnerability to climate variability. In the following years it began to be recognized that an integrated programmatic framework would have to be the central paradigm of both national and international programs that would be able to understand global change. Starting in 1985, a series of National Research Council reports called for an observing strategy that would focus on the highest priority measurements needed for each of the major disciplines of the Earth sciences. The reports stressed the need for simultaneity, calibration, and continuity of measurements to show how the Earth is changing and to develop and validate global predictive models. The Earth System Sciences Committee (ESSC), formed at NASA's behest, in 1988 called for a program of sustained long-term measurements of global variables. The Committee stressed that the measurements must be coupled to focused process studies and the development of Earth system models. The program must also include an information system that would ensure open access to consistent, long-term observations of the Earth system.

Now EOS is an integral element of the U.S. Global Change Research Program (USGCRP). Four key USGCRP global change issues are: 1) seasonal-to-interannual climate variability, 2) climate change over decades to centuries, 3) changes in ozone, ultraviolet radiation, and atmospheric chemistry, and 4) changes in land cover and in terrestrial and aquatic systems. In addition to these areas of particular scientific and practical importance, USGCRP has defined an overarching objective (often referred to as "human dimension") to identify, understand, and analyze how human activities contribute to changes in natural systems,



how the consequences of natural and human-induced change affect the health and well-being of humans and their institutions, and how humans could respond to problems associated with environmental change.

EOS science in support of the USGCRP is well described by the seven topical science chapters presented in this EOS Science Plan: Radiation, clouds, water vapor, precipitation, and atmospheric circulation; Ocean circulation, productivity, and exchange with the atmosphere; Atmospheric chemistry and greenhouse gases; Land ecosystems and hydrology; Cryospheric systems; Ozone and stratospheric chemistry; and Volcanoes and climate effects of aerosols.

EOS Science Contributions

EOS science contributions are too numerous to present in detail in this summary, but can be viewed for convenience as a means of obtaining global measurements (with appropriate characteristics) of the 24 variables listed in a table on the following page.

As pointed out in the text, EOS observations related to atmospheric phenomena will provide for validation on scales ranging from the size of cloud systems to regional to global and will support modeling efforts at these spatial scales as well as temporal scales ranging, correspondingly, from less than a day, to ten days, to 100 years. Several EOS interdisciplinary investigations are pursuing improved understanding of cloud-climate feedbacks where great uncertainties exist for predictions of climate change.

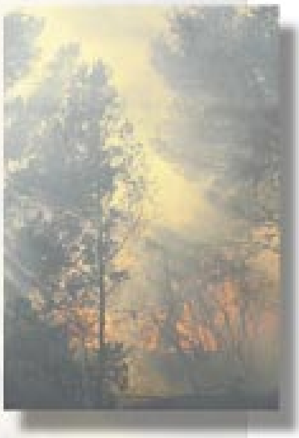
EOS measurements will shed new light on both physical and biological aspects of the world's oceans, including their circulation, their productivity, and their role in exchanging gases such as carbon dioxide with the atmosphere. EOS observations related to greenhouse gases and the chemistry of the lower atmosphere will lead to new understanding of the events that control the production of tropospheric ozone including the occurrence of biomass burning and the changes in land cover that are taking place worldwide.

EOS measurements of land ecosystems and hydrology will provide unprecedented worldwide coverage of vegetation extent and characteristics, thus improving our knowledge of terrestrial biospheric dynamics and vegetation process activity. Long-term consistent data sets related to the cryosphere will be able to document changes and validate transient model simulations using global climate models. EOS laser altimetry through repeated measurements will reveal changes in the surface elevation of ice sheets, and thereby improve our knowledge of changes in their mass balance with implications for sea-level rise.

EOS will contribute greatly, through measurements of trace gas chemistry and temperatures in the stratosphere, to our understanding of changes in the ozone layer and the related climate forcing. EOS will enable the first truly global inventory of volcanic eruptions with their implications for climate change through the introduction of stratospheric aerosols. In addition, timely EOS observations of volcanic phenomena can lead to significant warnings of hazards for people on the ground or for aircraft that may encounter volcanic plumes or clouds, possibly causing the aircraft to crash.

ATMOSPHERE	Cloud Properties *(amount, optical properties, height)*	**MODIS**, **GLAS**, **AMSR-E**, ***MISR***, ***AIRS***, ***ASTER***, EOSP, SAGE III
	Radiative Energy Fluxes *(top of atmosphere, surface)*	**CERES**, **ACRIM**, **TSIM**, **MODIS**, **AMSR-E**, ***GLAS***, ***MISR***, ***AIRS***, ASTER, SAGE III
	Precipitation	**AMSR-E**
	Tropospheric Chemistry *(ozone, precursor gases)*	**TES**, **MOPITT**, SAGE III, MLS, HIRDLS, LIS
	Stratospheric Chemistry *(ozone, ClO, BrO, OH, trace gases)*	**MLS**, **HIRDLS**, **SAGE III**, **OMI**, ***TES***
	Aerosol Properties *(stratospheric, tropospheric)*	**SAGE III**, ***HIRDLS*** **MODIS**, **MISR**, **EOSP**, ***OMI***, ***GLAS***
	Atmospheric Temperature	**AIRS/AMSU**, **MLS**, ***HIRDLS***, TES, MODIS
	Atmospheric Humidity	**AIRS/AMSU/HSB**, ***MLS***, ***SAGE III***, ***HIRDLS***, Poseidon 2/JMR, MODIS, TES
	Lightning *(events, area, flash structure)*	**LIS**
SOLAR RADIATION	Total Solar Irradiance	**ACRIM**, **TSIM**
	Ultraviolet Spectral Irradiance	**SOLSTICE**
LAND	Land Cover & Land Use Change	**ETM+**, **MODIS**, ***ASTER***, ***MISR***
	Vegetation Dynamics	**MODIS**, **MISR**, **ETM+**, ***ASTER***
	Surface Temperature	**ASTER**, **MODIS**, ***AIRS***, ETM+
	Fire Occurrence *(extent, thermal anomalies)*	**MODIS**, **ASTER**, ***ETM+***
	Volcanic Effects *(frequency of occurrence, thermal anomalies, impact)*	**MODIS**, **ASTER**, **ETM+**, ***MISR***
	Surface Wetness	**AMSR-E**
OCEAN	Surface Temperature	**MODIS**, **AIRS**, ***AMSR-E***
	Phytoplankton & Dissolved Organic Matter	**MODIS**
	Surface Wind Fields	**SeaWinds**, ***AMSR-E***, Poseidon 2/JMR
	Ocean Surface Topography *(height, waves, sea level)*	**Poseidon 2/JMR**
CRYOSPHERE	Land Ice *(ice sheet topography, ice sheet volume change, glacier change)*	**GLAS**, **ASTER**, **ETM+**
	Sea Ice *(extent, concentration, motion, temperature)*	**AMSR-E**, ***Poseidon 2/JMR***, MODIS, ETM+, ASTER
	Snow Cover *(extent, water equivalent)*	**MODIS**, **AMSR-E**, ***ASTER***, ***ETM+***

▲ **24 EOS Measurements**



National and International Contributions to Major Field Campaigns

EOS observations and modeling studies clearly will support numerous surface observation efforts and many major field campaigns. Just to list a few of these, there are the Global Energy and Water Cycle Experiment (GEWEX) , the Climate Variability project (CLIVAR) of the World Climate Research Program, and the Joint Global Ocean Flux Study (JGOFS) of the International Geosphere-Biosphere Program (IGBP)

EOS Measurement Strategy

EOS has developed a measurement strategy that includes:

- Simultaneity of observations taken by a group of sensors preferably on the same satellite platform or else closely coordinated in space and time;
- Overlap between measurements by successive sensors for intercomparison and intercalibration, in order to construct useful long-term climate records;
- Diurnal sampling to detect changes of rapidly varying systems such as clouds;
- High-quality calibration to permit intra- and intersystem data comparisons; and
- A data continuity strategy that ensures that successive sensors will maintain a data stream for long-term analyses of changing phenomena.

EOS Contributions to National Goals and Needs

The remainder of this chapter is devoted to a demonstration of the response of EOS to “National Goals and Needs” as defined by the five USGCRP themes presented at the beginning of this summary. For each theme, “the national interest” is presented along with the related “national policy requirements,” and then the “EOS Policy-Relevant Contributions” are given in terms of measurements by the EOS sensors and assessments based on EOS interdisciplinary studies. Notably, EOS studies will provide a realistic basis for understanding the potential rate and magnitude of global change in all its aspects as it affects the world around us and the people of our Earth.

Chapter 2

Radiation, Clouds, Water Vapor, Precipitation, and Atmospheric Circulation

Introduction

Chapter 2 focuses on the role of radiation, clouds, atmospheric water, precipitation, and atmospheric circulation in determining climate and global change. The chapter begins with a discussion of major scientific issues involving each of the relevant climate areas and how they affect climate. Then, for each climate area, there is a discussion of the required satellite and field measurement programs. The chapter ends with a review of anticipated EOS contributions to improving our knowledge of the key climate variables and data sets.

Background

The temperature near the surface of the Earth is in thermodynamic equilibrium when the absorption of radiant energy from the sun is in approximate balance with the emission of radiant energy to space from the Earth. Thus, the energy output of the sun provides a critical control on the Earth's climate. The amount of the solar energy that is absorbed by the Earth depends on Earth's reflectivity, and the reflectivity is strongly dependent on the fractional coverage and optical properties of clouds in the atmosphere, the amount and optical properties of aerosol particles in the atmosphere, the atmospheric humidity, and the condition of the surface.

The surface temperature of the Earth depends not only on the absorbed solar radiation but also on the rate at which energy is reradiated to space from the Earth. The rate of reradiation is controlled by both the amount and the vertical distribution of not only the clouds and aerosol particles but also the amount and distribution of the greenhouse gases in the atmosphere, of which the most important is water vapor. The water vapor distribution interacts strongly with convection in the atmosphere and the associated clouds, precipitation, and large-scale circulations. The water vapor distribution also interacts strongly with the thermal structure of the atmosphere.

Understanding the interactions among the various elements listed above and incorporating this understanding into appropriate models constitutes a critical step in predicting future climate changes and their regional and global impacts. Likewise, improved understanding in these areas will help in the prediction of seasonal and interannual climate variability. Beyond the confines of the atmosphere there are also interactions with the oceans to be considered, and these are strongly modulated by clouds, water vapor, and large-scale circulations.

Total Solar Irradiance

The energy from the sun that is available to be received at the average distance of the Earth from the sun is called total solar irradiance (TSI) and is specified in watts per square meter (Wm^{-2}). Long-term solar monitoring from space began with the Earth Radiation Budget (ERB) experiment in late 1978 and has continued into the present time frame with measurements from the Active Cavity Radiometer Irradiance Monitor II (ACRIM II) on NASA's Upper Atmosphere Research Satellite (UARS). Consistent measurements by ACRIM instruments I and II have shown variations in TSI running from a low of about 1367 Wm^{-2} at a solar cycle minimum in 1986 to a high of about 1369 Wm^{-2} in 1992 at a solar cycle peak. Although these changes appear small, it has been shown (Rind and Overpeck, 1993; Lean et al., 1994) that sustained changes in TSI of as little as a few tenths of one percent could be causal factors for significant climate change on time scales ranging from decades to centuries. Climate changes comparable to the "Little Ice Age" may involve TSI changes as small as 0.5% over 200+ years.

The Role of Radiation Fluxes in the Climate System

The climate system is a heat engine that is driven by the spatial and temporal displacement of the entry and exit of broadband radiant energy. Radiation is the primary forcing element in climate change. A net flow of radiant energy at the top of the atmosphere enters the tropics and leaves at high latitudes. The resulting equator-to-pole heating gradient drives the circulations of the atmosphere and ocean. The largest fraction of radiant energy entering the climate system is absorbed at the surface in the form of solar radiation, but leaves the atmosphere in the form of thermal infrared emission. This radiative heating below and cooling above drives the convective activity of the troposphere, resulting in abundant rainfall and cleansing of the atmosphere.

Radiation is important for climate feedback. Uncertainties in the radiative feedback to climate by clouds pose the most formidable obstacle to climate prediction by general circulation models (GCMs). Because of the uncertainty in the cloud/climate feedback to changes in radiation at the top of the atmosphere (TOA) we cannot reliably predict the climate response to a given radiative forcing. However, there have been fairly good simulations of transient temperature variations to the radiative forcing due to the aerosol plumes that resulted from the 1991 Mt. Pinatubo eruption (Hansen et al., 1994).

Atmospheric gases have a greater effect on the climate than any other component of the Earth's climate system. It is estimated that absorption of infrared radiation by atmospheric gases reduces the escaping longwave radiation by about 120 Wm^{-2}, whereas the reflection of solar radiation by clouds and the surface each return only about 50 Wm^{-2} to space, when globally averaged. Modern climate models have consistently indicated that CO_2 and other anthropogenic traces gases will change the vertical distribution of radiative fluxes in the atmospheric column so as to warm the troposphere and cool the stratosphere.

Top-of-the-atmosphere shortwave and longwave radiative fluxes are used to derive surface radiative fluxes. Currently available results from the Earth Radiation Budget Experiment (ERBE) seem to have an error of about 5 Wm^{-2} , which presumably contributes to even larger errors in surface radiative fluxes.

EOS will contribute to improved understanding of the effects of the atmospheric gases by producing more-accurate vertical profiles and time histories of water vapor and radiative active gases and by validating the radiative transfer physics for both the natural and anthropogenic gases in the atmosphere. Ellingson et al. (1991) have shown that there are still significant problems with the calculation of broadband radiative fluxes in the atmosphere for a given distribution of atmospheric gases.

Both the direct and indirect radiative effects of aerosols constitute the largest uncertainties in the anthropogenic radiative forcing of climate. Anthropogenic sulfate aerosols mostly scatter shortwave radiation and cool the climate. Smoke from biomass burning may have a global cooling effect of 0.2 to 2 Wm^{-2} .

Clouds are second only to greenhouse gases in terms of their effect on climate. However, there is great uncertainty about cloud radiative forcing and feedback (Cess et al., 1991). Estimating the radiative effects of clouds and retrieving cloud properties from space both require a detailed understanding of the scattering and absorption properties of clouds. Important problems remain in modeling the directional scattering of solar radiation by clouds, the radiative effects of the overlap of cloud fragments, and perhaps even in the basic absorption properties of cloudy atmospheres. The EOS instrument CERES, along with other EOS instruments such as MISR and EOSP, is expected to provide significant advances in the estimate of radiative forcing by clouds. EOS will begin to resolve problems caused by cloud overlap and cloud geometrical thickness through use of both passive and active sensors.

The long homogeneous record of clouds and radiation fluxes to be provided by EOS in the course of 15-18 years of observations will allow seasonal and interannual variability to be sampled adequately and will be used to understand connections within the climate system that only appear on longer time scales.

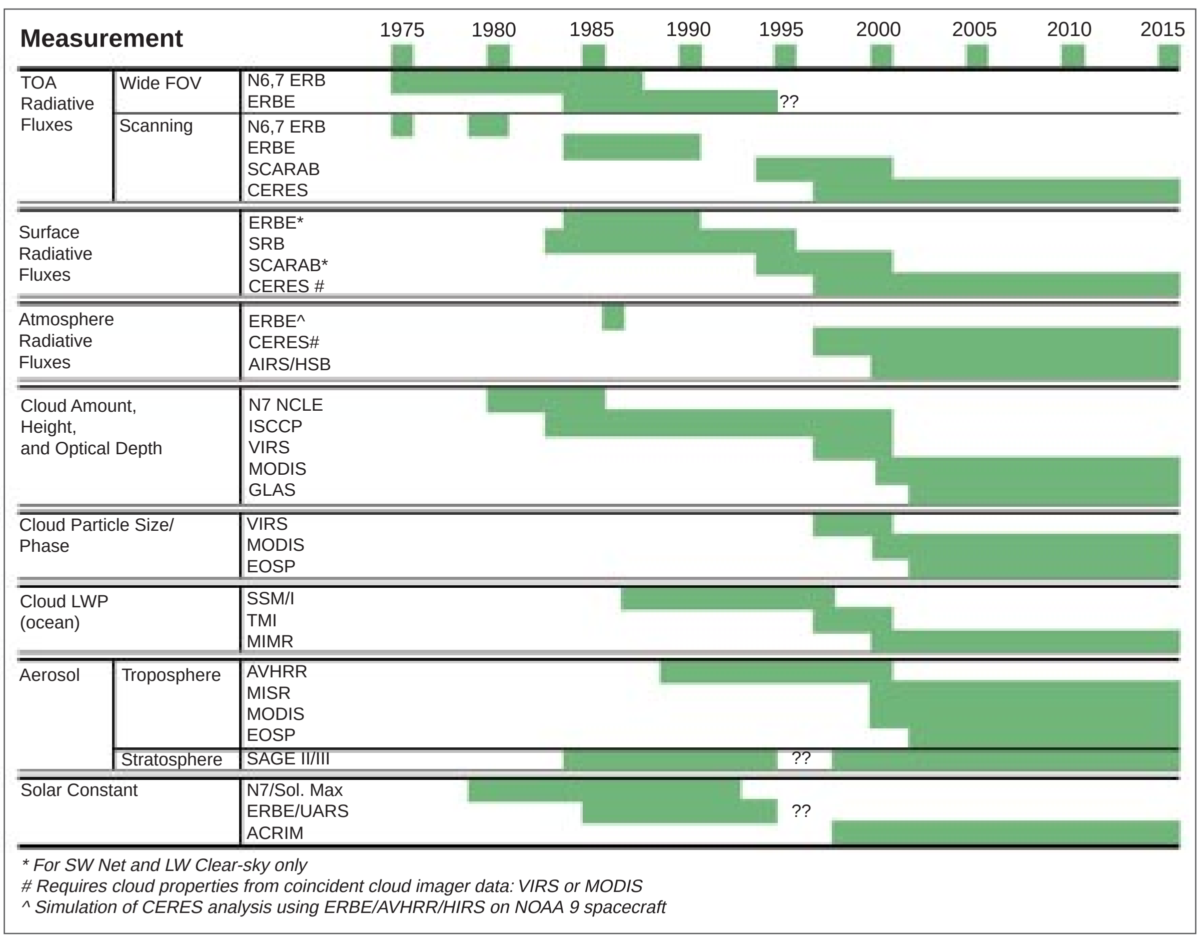
The surface of the Earth absorbs about twice as much solar radiation as does the atmospheric column above. The amount of solar radiation that is absorbed by the surface is modulated by a surface solar albedo that ranges from 0.06 for diffuse radiation striking the ocean to approximately 0.90 for some of the freshest snow. The GEWEX Surface Radiation Budget (SRB) Project has found that errors in both shortwave and longwave radiation over snow and ice surfaces and for longwave radiation in persistently cloudy regions are larger than those in other regions. There are problems in satellite determinations that require distinguishing between clouds and snow-covered surfaces. Surface albedos and radiative fluxes over snow-free land are also not known to sufficient accuracy. Until EOS determines the surface albedo of all land surfaces to greater accuracy, it will not be possible to quantify adequately the radiative forcing to climate that is associated with changes in land use.

The surface energy budget provides a key forcing to ocean circulation so that more-accurate information is needed in this aspect of radiation studies as well. Downwelling longwave radiation measurements over the extratropical oceans will be a limiting factor for EOS sensors. The retrieval of this radiation will be improved by combining satellite measurements with data from ocean-based monitoring stations that would provide both surface radiation budget and cloud-base heights.

The Role of Convection and Clouds in Climate

Clouds not only affect the radiative energy fluxes in the atmosphere through scattering, absorption, and reradiation but also vertical motions associated with them produce important convective transports of energy and moisture. Interactions of clouds with the clear environment around them play a critical role in determining both the amount of water vapor that is retained in the clear atmosphere and the amount of precipitation reaching the surface. The influence of clouds on the radiation balance of the Earth was estimated by the Earth Radiation Budget Experiment (ERBE; Ramanathan et al., 1989; Harrison et al., 1990). These estimates revealed that if clouds were suddenly removed and nothing else changed, there would be a net positive change in the energy balance of the Earth of about 20 Wm^{-2} . It is recognized that clouds represent a redistribution of energy between the surface and the atmosphere that may be larger than the net effect of clouds on the energy balance at the top of the atmosphere. Convection associated with clouds also affects the exchange of heat between the surface and the atmosphere.

Timeline of the primary global and regional satellite observations for clouds and radiative properties *(Wielicki et al., 1995, reproduced with permission from the American Meteorological Society).*



	Past and Current	Time Span	Cloud and Radiation	Time Sampling (Eq. crossing, LT) Observations	Monthly Average Grid	Nadir Field of View (km)	Data Source
Pre-EOS	N7 ERB	1979-1990	SW, LW fluxes: top of atmosphere	1200	500 km	90; 1000	NSSDC
Pre-EOS	N7 New Cloud/ERB	1979-1990	Cloud amount, height	1200	500 km	8; 60	NSSDC
Pre-EOS	HIRS	1989-1993	Cirrus height, emittance	0700, 1400	2.5°	20	NOAA
Pre-EOS	ERBE	1984-1995+	SW, LW fluxes: top of atmosphere, cloud forcing	0700, 1400, Precessing	2.5°	40; 1000	LaRC V0 DAAC
Pre-EOS	ISCCP	1983-1995+	Cloud amount, height, optical depth	Every 3 h	280 km	4-8	LaRC V0 DAAC
Pre-EOS	SRB	1983-1995+	SW, LW fluxes: surface	Every 3 h	280 km	4-8	LaRC V0 DAAC
Pre-EOS	SSM/I	1987-1995+	Cloud liquid water path (ocean only)	0630, 1630	1.0°	32-55	Wetnet
Pre-EOS	SCARAB	1994-1997+	SW, LW fluxes: top of atmosphere	Precessing	2.5°	80	CNES/France
TRMM (45°N-45°S)	CERES	1997-2000	SW, LW fluxes: top of atmosphere, surface,* in atmosphere*	Precessing	1.0°	10	LaRC V1 DAAC
TRMM (45°N-45°S)	VIRS	1997-2000	Cloud amount, height, optical depth, particle size/phase	Precessing	1.0°	2	LaRC V1 DAAC
TRMM (45°N-45°S)	TMI	1997-2000	Cloud liquid water path (ocean only)	Precessing	TBD	4.5-37	TBD

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Primary global and regional satellite observations of clouds and radiation in the pre-EOS and EOS era. Satellite data with 1/8 to 2-day coverage, and both day and night observations *(Wielicki et al., 1995, used with permission from the American Meteorological Society).*

Modeling of the atmosphere including clouds is currently conducted on three scales: these are global, regional, and cloud-resolving, and the corresponding horizontal resolutions range from 100 km (global), to about 10 km (regional), to about 1 km (cloud resolving). EOS observations will provide data for validation on all of these horizontal scales, and EOS interdisciplinary investigations will be conducted at all these scales. The model runs can range from 100-year integrations (global), to 10-day integrations (regional), to 1-day (cloud resolving).

There are many questions regarding cloud characteristics that are faced by climate modelers. The cloud type that appears to exert the greatest effect on climate sensitivity in state-of-the-art global general circulation models (GCMs) is the tropical mesoscale anvil cloud that accompanies cumulus convection (Heymsfield and Donner 1990; Del Genio et al., 1995). The central question is how to represent the detrainment of ice from cumulus updrafts into anvil clouds. Among many EOS instruments that will contribute to answering this question are several that will help define cloud characteristics and, in particular, LIS, whose lightning occurrence record

will serve as an index of convection intensity, and AIRS, whose temperature and moisture profiles will yield estimates of convective available potential energy.

Many atmospheric circulation systems are organized on the regional or mesoscale (defined as encompassing horizontal length scales of 20-200 km). Mesoscale convective systems dominate weather over most of the tropics and the summertime midwestern United States. Mesoscale models (MMs) have become powerful tools for understanding and forecasting regional atmospheric circulations, taking into account such features as severe midlatitude cyclones, hurricanes, orographically forced flow, fronts, and thermally forced flows such as land/sea breezes.

The increased use of MMs has particular promise in the areas of tropical convection, cirrus cloud evolution, midlatitude cyclonic cloud systems, and prediction of boundary-layer fog and cloud prediction. Several EOS interdisciplinary investigations are pursuing improved understanding of cloud-climate feedbacks. The higher spatial resolution, availability of new cloud variables, and greater accuracy of EOS cloud observations will enable better validation of regional cloud simulations.

Cloud-resolving models are also known as cumulus ensemble models (CEMs). They include explicit representations of many aspects of cloud microphysics. A typical CEM has a spatial resolution of 1-3 km and variable vertical resolution of 0.2 to 1 km, with finer resolution in the atmospheric boundary layer and coarser resolution in the upper troposphere or lower stratosphere above cloud top.

CEMs include cloud-scale dynamics, subgrid-scale turbulence, and explicit computation of latent heating. The budgets of all three phases of water are also explicitly computed. CEMs have been coupled to oceanic mixed-layer models to elucidate the mechanisms of diurnal variability of clouds and precipitation over the oceans.

Radiative flux determinations are the highest priority measurements that are needed to understand the role of cloud feedback mechanisms in the climate system. At this time net radiative energy flux determinations at the top of the atmosphere (TOA) need to be supplemented by the more-difficult determinations of the net radiative energy flux at the Earth's surface. The vertical distribution of radiative cooling/heating inside the atmosphere is also very important. In order of priority are the TOA radiative flux, the surface radiative flux, and the radiative flux at the tropopause. In order to improve simulations of cloud forcing and its effect on climate sensitivity, more-detailed measurements of cloud properties are needed to provide understanding and model validation.

TOA radiative flux measurements from space will enter their fourth generation with the CERES instruments on TRMM and on the EOS AM-1 and PM-1 spacecraft. The most recent ERBE measurements provide the standard of comparison for global radiation data sets. The CERES measurement errors are expected to be a factor of 2-4 lower than the ERBE errors.

Global satellite estimates of radiative fluxes at the surface (up, down, and net) are now becoming available. There are two independent approaches for determining surface radiative fluxes: 1) Use observed cloud and atmosphere parameters with measured TOA broadband fluxes acting as a constraint on the radiative calculations, and 2) Use parameterized relationships between simultaneously observed TOA fluxes (or radiances) and surface fluxes.

In the EOS time frame calculated shortwave surface flux accuracies should increase greatly as more-accurate cloud (VIRS, MODIS), atmospheric (AIRS), and surface (MISR, MODIS) properties become available. Downward longwave fluxes present a greater problem. In the EOS time frame improved tropospheric water vapor determinations will help. They will be available from the AIRS/HSB instruments and, over land, from MODIS.

Cloud overlap may be the largest uncertainty for calculations of downward longwave flux at the surface. In the long term, active systems such as the GLAS lidar from EOS and a proposed 94-Ghz cloud radar may offer the best solution. Remotely piloted aircraft will be of great help in testing with-the-atmosphere flux calculations.

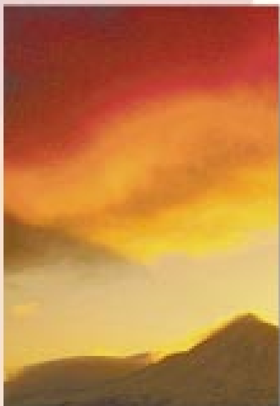
Measurements of cloud properties are very difficult. The EOS MODIS instrument has design capabilities specifically directed toward cloud-property determinations. Very-high-spatial-resolution measurements from EOS ASTER, multi-angle EOS MISR data, determinations of the polarization of cloud particles from EOS EOSP, all will contribute to the validation of the MODIS data. The final step in cloud remote sensing during the EOS era will be the combination of the passive sensors just cited with EOS GLAS (the active lidar sensor) and the proposed cloud radar.

Other cloud properties that will be the subject of investigation in the EOS era include cloud fraction, cloud visible optical depth and thermal infrared emittance, cloud particle size, cloud liquid/ice water path, and cloud mesoscale organization and structure. Improved spectral resolution (including solar, terrestrial infrared, and microwave coverage) and spatial resolution, multi-angle coverage, and the use of both passive and active sensors will lead to various degrees in improvements in the determinations of these cloud properties.

Water Vapor and Climate

Most of the water in the atmosphere is in the form of vapor, and water vapor plays a critical role in many key processes in the hydrologic and energy cycles. Water vapor is the most important greenhouse gas, both in terms of its role in maintaining the current climate and in terms of its role in sensitivity through the water vapor feedback process. The abundance and vertical distribution of water vapor in the atmosphere interact very strongly with convection and cloudiness, thereby influencing the albedo of the planet as well as the infrared opacity of the atmosphere.

Data from EOS instruments will improve the quality of global measurements of the water vapor distribution. In particular, the EOS instruments, AIRS, AMSU, and HSB, working in combination, will provide more-precise simultaneous measurements of temperature and humidity in the troposphere, with better vertical resolution than is currently available. Climate feedbacks are sensitive to the vertical distribution of both water vapor and temperature. EOS cloud and moisture measurements, when combined with wind estimates from data assimilation tech-



niques and with in situ measurements from field programs, will provide a much better understanding of the mechanisms whereby the moisture balance of the troposphere is maintained.

Surface temperatures are related to the global distribution of water vapor. For instance, sea surface temperatures (SST) are highly correlated with the water vapor over the ocean.

Climate models are only beginning to account explicitly for cloud water and ice, their transport, and their evaporation to provide a source of water vapor in the free atmosphere. EOS data will play an important role in validating the new generation of climate models that incorporate these features.

In every respect, the water vapor data sets available to date are inadequate for climate studies. Radiosondes are limited in their geographic coverage, and satellite retrievals suffer from poor vertical resolution and accuracy. Besides the improvements in temperature and moisture profiles to be offered by AIRS/AMSU/HSB, the EOS instruments HIRDLS and MLS will supply improved horizontal and vertical resolution measurements. Also, the EOS SAGE III instrument will provide very accurate monitoring of water vapor trends in the stratosphere.

Precipitation

Rainfall plays a central role in governing the climate of the Earth. The latent heat release in convection is the main source of energy that drives the general circulation of the atmosphere, since much of the solar radiation absorbed by the Earth is used to evaporate water, which later condenses to release latent heat in the atmosphere during precipitation. Latent heat release in tropical convection forces atmospheric motions that disperse heat and moisture into the extratropics, diverting subtropical jetstreams and altering rainfall patterns in midlatitudes.

The distribution of precipitation is highly inhomogeneous in space and time. Because of the wide range of variability in both time (minutes to years) and space (less than a kilometer to thousands of kilometers) the long-term accurate mapping of global precipitation is a daunting task. Atmospheric models have been show to be able to produce a global precipitation rate to within 10-20% of that observed, but they have many serious faults otherwise. They differ particularly in their ability to estimate regional and subcontinental rainfall variability. They also underestimate the frequency of occurrence of the light-rain category. Because it is impossible to set up uniform networks of rain gauges over the entire globe, satellite rainfall retrieval algorithms will play a vital role in producing realistic global rainfall distributions.

As part of the Earth Science Enterprise, The Tropical Rainfall Measuring Mission (TRMM) launched in November 1997 employs a suite of sensors including one microwave (TMI), one VIS/IR (VIRS), and one active precipitation radar (PR) with the objective of producing the best rainfall estimates from space, especially for the world's tropics. Within the EOS measurement system, the key instruments for precipitation measurement are AMSR-E and HSB on the EOS PM-1 platform.

Atmospheric Circulation, Hydrologic Processes, and Climate

The presence of clouds, water vapor, and precipitation in the atmosphere significantly alters the Earth's radiation budget and causes differential heating between the tropics and the polar regions, between the oceans and the land, and between clear and cloudy regions. This differential heating is the main driver of the atmospheric large-scale circulation, and the essential component of the circulation is the wind. The consideration of the atmospheric wind circulation is indispensable in order to understand the role of the global hydrologic cycle, clouds, water, and precipitation on regional and global climate fluctuations.

It is well recognized that while radiative forcings such as that due to doubling of CO_2 may be small, feedback processes in the climate system may amplify the initial response to the radiative forcing. Especially for climate changes on seasonal and interannual time scales, the large-scale circulation plays a fundamental role.

The EOS SeaWinds instruments on QuikSCAT and successive Japanese ADEOS spacecraft will provide surface wind speed and direction over the oceans from scatterometry, and EOS passive microwave radiometry, using AMSR-E, will contribute to wind determinations over the ocean as well.

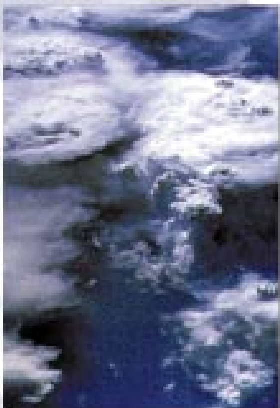
Required Satellite Measurements and Data Sets

Total solar irradiance—By using overlapping flights of the EOS ACRIM instrument, with 0.1% absolute accuracy, it is believed that a relative precision of 0.001% can be achieved, and that this relative precision would be sufficient to detect climatically significant changes in total solar irradiance on time scales of up to a century.

Radiative fluxes—The expected changes in climate forcing due to solar irradiance changes are about 0.25 Wm^{-2} , and the expected climate forcing from doubling CO_2 is about 4 Wm^{-2} . On the other hand variations of radiative fluxes within the climate system that are associated with season, location, weather, or natural interannual variability are much larger, often on the order of 100 Wm^{-2}. Current climate models appear to be in error by tens of Wm^{-2} so that an achievable accuracy of 5 Wm^{-2} is very useful despite being larger than the expected climate forcings.

CERES has been designed to measure the total radiative energy flux, and MODIS has been designed with both high spectral and spatial resolution in order to understand what causes changes in radiative flux that may be due to changes in temperature, clouds, aerosols, water vapor, or other greenhouse gases. Changes in radiances due to solar and satellite viewing angles need to be taken into account, and MISR's ability to view pixels as small as 275 m from 9 angles is an important contribution. The CERES design also makes angular sampling of radiances possible.

There is an important systematic variability of radiative fluxes on the diurnal time scale. For this reason CERES is to fly on two sun-synchronous platforms, EOS AM-1 and EOS PM-1, simultaneously, and, in addition, on the precessing platform, TRMM. With this scheme there are to be observations of most points on the Earth at six local times each day.



With CERES and cloud imagers such as MODIS or VIRS (on TRMM) it will be possible to provide TOA flux measurements with an estimated absolute accuracy of 2.5 Wm^{-2} for longwave and 5 Wm^{-2} for shortwave radiation. Estimation of surface and internal atmospheric fluxes requires inclusion of temperature, water vapor, and cloud measurements from the EOS instruments in model calculations. Accuracies to be achieved are less certain than for fluxes at the top of the atmosphere.

Cloud properties—Cloud properties are derived by many of the EOS instruments:

- MODIS is the prime instrument for EOS cloud property measurements, with roughly 12 cloud spectral channels and 0.25-1 km fields of view.

- With extremely high spatial resolution, ASTER is used to verify the effects of sub-pixel cloud variations on MODIS global cloud retrievals. ASTER has eight cloud spectral channels and 15-90 m spatial resolution for selected 60-km regions.

- MISR has 9 multi-angle view angles functioning in 4 solar spectral channels. It is used for narrowband cloud anisotropy measurements as well as stereo cloud heights for broken cloud fields.

- The high spectral resolution of AIRS, with up to 2300 infrared spectral channels, permits measuring the spectral variation of cloud emittances. AIRS measurements also serve to confirm interpretations of cloud particle phase and size based on MODIS measurements.

- EOSP is unique in its measurement of reflected solar radiation polarization. Its measurements are useful at small optical depths and for cloud particle size and phase estimation. Along with MISR it may provide information on ice crystal shape.

- GLAS is the active lidar instrument useful for remotely sensing cloud height and base of optically thin clouds.

- SAGE III and HIRDLS are used for height measurement and detection of extremely thin clouds in the upper troposphere or stratosphere. These are clouds that might otherwise go undetected.

- CERES data are used to constrain cloud property retrievals and, working with MODIS or VIRS, to provide radiatively consistent sets of cloud and radiation data.

- VIRS on TRMM, with 5 spectral channels and a 2-km nadir field of view, provides an advance over the current AVHRR instrument for cloud measurements.

The macroscopic properties of clouds that will be determined by the EOS instruments include cloud fractional area coverage, cloud height, cloud visible optical depth, and infrared emissivity. At the cloud physics level, the EOS instruments will provide information on cloud particle size and particle phase. It is anticipated that the effective radius of cloud particles may be obtained with an accuracy of about 1.25 mm. (This is the accuracy required to give an accuracy in absorbed solar radiation of 5 Wm^{-2}.)

Lightning flashes—The detection of lightning flashes by LIS on TRMM will contribute to a global survey of thunderstorm occurrences and cloud electrification processes.

Atmospheric temperature profiles—The AIRS instrument was designed to provide a significant benefit to weather forecasting efforts by providing temperature profiles with an accuracy of 1 K for vertical scales on the order of 1 km. The addition of AMSU microwave channels improves the AIRS capability to provide accurate temperature profiles under partly cloudy conditions. The addition of HSB to the AIRS sounding complement improves soundings of both temperature and humidity in the presence of clouds.

Water vapor—An accuracy of 5-10% for water vapor mixing ratios is required for layers of about equal height at all levels of the atmosphere. The AIRS/AMSU/HSB instrument complement will provide adequate measurements for the lower troposphere, and the EOS limb-viewing instruments, SAGE III, HIRDLS, and MLS, provide good vertical resolution and precision in the upper troposphere and lower stratosphere.

Precipitation—The primary technology for estimating precipitation globally during the EOS period will be passive remote sensing from a microwave imager such as MIMR (for ESA) and AMSR-E for EOS. The obtainable accuracies may be less than required, but still will represent an improvement over current estimates. Precipitation estimates for the tropical and subtropical regions will also be available from the passive imager (TMI) and the active precipitation radar (PR), both on TRMM.

Winds and circulation—Scatterometers, such as the EOS SeaWinds, scheduled to fly on QuikSCAT and on the Japanese ADEOS spacecraft, will be able to provide surface winds over the oceans with an accuracy of 10% for wind speed and a 20˚ random error. No direct measurements of wind speed are planned for the free troposphere or the atmospheric boundary layer over land, although it is recognized that such measurements would be very desirable.

Supporting Surface Observations and Field Experiments

Satellite observations must necessarily be supplemented by field experiments. Many necessary experiments are incorporated in major field experiments to be enumerated below. These experiments are vital for: 1) assessing the accuracy of satellite-derived geophysical parameters; 2) evaluating the precision and accuracy of satellite instrument calibration; and 3) providing enhanced information on the characteristics of surface and atmospheric constituents assumed in the remote-sensing

retrievals that are made using satellite observations. Following are a few of the major field programs that will provide support to the satellite measurements.

FIRE—The First ISCCP Regional Experiment (FIRE) is an ongoing multi-agency international program to support the development of improved cloud radiation parameterization schemes. The program has focused so far on marine stratocumulus clouds and cirrus clouds. Marine stratocumulus clouds exert a large influence on the radiation balance of the Earth-atmosphere-ocean system through their large areal extent, temporal persistence, and high reflectivity to solar radiation. Cirrus clouds exert their greatest radiative influence on the Earth's climate through their effects on longwave radiation emitted to space. The intensive field campaigns that have been conducted as part of FIRE have shown that there are still discrepancies between remote sensing and in situ estimates of various aspects of cloud properties.

GEWEX—The Global Energy and Water Cycle Experiment (GEWEX) focuses on observing and modeling the hydrologic cycle and energy fluxes in the atmosphere, at the land surface, and in the upper layers of the oceans. It has a validation component that will assist in assessing the accuracy of satellite schemes for remote sensing of atmospheric temperature and moisture profiles, vertically integrated water vapor, cloud base altitude, surface longwave flux and cloud optical and microphysical properties.

CLIVAR—The CLIVAR (for climate variability) project is part of the World Climate Research Program (WCRP) and seeks to understand and predict climate variability on interannual-to-centennial time scales.

ARM—The Atmospheric Radiation Measurement (ARM) Program is the largest contribution of the Department of Energy (DOE) to the United States Global Change Research Program (USGCRP). It is a sophisticated measurement program using ground-based facilities as well as remotely piloted aircraft to characterize the broadband and spectral components of both longwave and shortwave radiation reaching the Earth's surface, as well as measure the water vapor, temperature, and wind profiles throughout the lower atmosphere. ARM will have facilities at three key locales around the world, providing three distinct climatological regimes: 1) the Southern Great Plains of the United States, 2) the western tropical Pacific, and 3) the north slope of Alaska.

BSRN—The Baseline Surface Radiation Network (BSRN) is an international program of the World Climate Research Program designed to improve the accuracy and sampling rate of surface-measured shortwave and especially longwave radiative fluxes. Ultimately, there are to be about 30 sites in the network providing not only the shortwave and longwave fluxes, but also synoptic and upper air observations as well.

ECLIPS—The Experimental Cloud Lidar Pilot Study (ECLIPS) will obtain observations of cloud-backscattering profiles from about 10 ground-based lidar sites around the world. They will provide cloud base altitudes for all cloud types including cirrus, and, in addition, they will provide cloud top altitudes for optically thin clouds.

Interactions with Oceans and Land Processes

Oceans—The storage and transport of heat by the oceans are strongly affected by surface forcing of momentum, heat, and moisture through interactions with the atmosphere. EOS scatterometry and passive microwave imaging can give surface wind stress over the oceans, and this is the key to momentum, heat, and moisture exchange rates. EOS spaceborne sensors will provide the most viable method of monitoring the radiative and turbulent heat fluxes at the surface of the oceans, and these make up the thermal forcing of the oceans.

Adequate resolution of meridional heat transport by the oceans requires an absolute accuracy of better than 10 Wm^{-2} in total heat flux, and it is expected that the EOS sensors will fulfill this requirement.

Monitoring of ocean surface solar irradiance, together with observations of ocean color by EOS sensors will advance our understanding of the biogeochemical cycles in the ocean.

Land Processes—Information on all components of the surface radiation budget is vital for land surface studies, covering the gamut from land surface climatology to ecology. Similarly, information on precipitation and evaporation is needed for the understanding of the availability of surface moisture for plants, animals, and people, and knowledge of the large-scale circulations is essential to understanding the exchange of moisture and gaseous compounds of importance between land areas and the rest of the globe.

Summary of EOS Contributions

EOS will provide an unparalleled opportunity for long-term observation and monitoring of key climate variables such as total solar irradiance; radiative energy fluxes at the top of the atmosphere, at the surface, and in the atmosphere; cloud properties; and precipitation. It will also provide improved understanding of the processes that relate clouds and water vapor to global climate and their effect on climate sensitivity; and also provide more-accurate treatment of clouds and water vapor and their radiative effects in global climate models. There will be better measurements of precipitation and consequent improved understanding of the role of precipitation in connecting atmospheric and surface processes and more-accurate modeling of precipitation in global climate models. Improvements in observational knowledge and understanding of atmospheric elements and processes will interact very positively to improve understanding and simulation of land surface and oceanic processes.

The global homogeneous long-term measurements of the climate system to be provided by EOS will result in enhanced assessment of global change and ultimately result in improved ability to predict seasonal and interannual climate variability. Through EOS there will be great enhancements in our ability to understand and predict global climate changes and their effects on human activities.

Chapter 3

Oceanic Circulation, Productivity, and Exchange with the Atmosphere

Introduction

Chapter 3 focuses on these scientific themes: the interaction between the atmosphere and ocean across the sea surface, including the role of the oceans in the Earth's heat and hydrologic cycles; ocean circulation and sea-level change; and the ocean's biological system and its interplay with the Earth's carbon cycle. The chapter reviews the important scientific issues and the observational requirements for each theme.

The Earth Observing System (EOS) will contribute to all the areas of scientific concern relating to the oceans not only through observations but also through a number of major interdisciplinary modeling studies making use of the observational data. Crucial to the understanding of ocean dynamics will be worldwide observations of ocean surface wind stress by the EOS SeaWinds scatterometer instrument, with accuracies of 10-12% in speed. In addition, the EOS AMSR-E passive microwave instrument will provide complementary continual observations of wind speeds and stress magnitudes over the oceans.

The role of the oceans in the Earth's heat and hydrologic cycles will be brought out in part by surface temperature measurements. The EOS MODIS instrument will provide sea-surface temperature (SST) measurements, based on infrared emissions from the oceans, for cloud-free conditions to the level of a few tenths of kelvin. The EOS AMSR-E will provide SST measurements, based on microwave emissions from the oceans, with an accuracy of 1-1.5 K in all weather conditions.

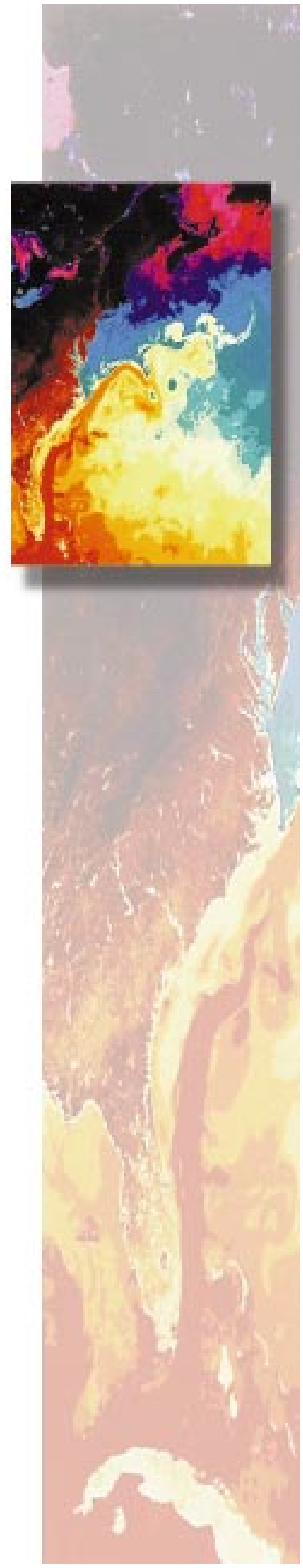
Several Interdisciplinary Science (IDS) investigations will be dedicated to studies of ocean circulation and sea-level changes. In addition, the EOS Jason-1 radar altimeter will contribute to the determination of multi-decadal global sea-level variations and their long-term trends; and EOS AMSR-E and SeaWinds measurements will contribute wind stress information as above.

IDS studies of the ocean's biological system and its interplay with the Earth's carbon cycle will be investigated by several teams which are synthesizing ocean and atmospheric circulation models. The EOS Moderate-Resolution Imaging Spectroradiometer (MODIS) instrument and the Earth Science Enterprise instrument, SeaWiFS, will acquire long-term, calibrated satellite data sets of ocean biogeochemical variables, particularly through those measurements that are called "ocean color." Their data will be supplemented by similar measurements made with the Ocean Color and Temperature Scanner (OCTS), Medium-Resolution Imaging Spectrometer (MERIS), and Global Imager (GLI) instruments that are provided by our international partners.

Background

The oceans play a key role in modulating global climate. About half of the Earth's absorbed solar radiation is absorbed by the World Ocean, which is an equal partner with the atmosphere in moderating the equator-to-pole temperature distribution by shifting to middle and high latitudes some of the excess heat gained in the tropics. The ability to forecast well in advance the timing and geographic extent of seasonal-to-interannual climate anomalies is predicated on properly representing the role of the ocean, which provides the thermal inertia of the climate system because of its immense and dominant heat capacity.

The oceans also play a key role in moderating the effects of increased carbon dioxide emissions on global warming. This is because they serve as a "sink" for much of the carbon dioxide emitted into the atmosphere by both human activities and natural phenomena. Part of the carbon dioxide taken up by the ocean supports the growth of the food chain, and part is sequestered in the depths of the ocean.



Major Scientific Questions Related to Ocean-Atmosphere-Surface Coupling

Three areas of concern related to ocean-atmosphere-surface coupling are momentum exchange, radiative and turbulent thermal fluxes, and freshwater forcing by evaporation, precipitation, and sea-ice growth and melt.

The exchange of momentum between the atmosphere and the ocean plays a critical role in climate. Wind stress patterns determine the large-scale upper-ocean circulation and the major current patterns that transport heat from low to high latitudes and moderate mid- and high-latitude surface temperatures that determine weather in much of the industrialized world. This stress also determines the strength of surface mixing and to what extent warm surface water is mixed with cooler waters from below. It helps determine the shape of the sea surface and local mean sea level.

The mean thermal fluxes at the ocean surface show a net radiative heating from the sun balanced mostly by evaporative cooling, that is, by the latent heat of evaporation. It has been shown that decadal-to-centennial variations in the thermohaline circulation of the ocean depend on exchanges of heat and water with the atmosphere. Simple atmospheric boundary-layer models can explain much of the observed pattern of sensible and latent heat fluxes over the global oceans. In the data-sparse areas of the southern, tropical, and ice-covered oceans, satellite observations will provide the first reliable estimates of the radiative fluxes and, when combined with boundary-layer models, of turbulent fluxes.

Freshwater forcing is an important aspect of the global water balance. The ocean loses about ten percent more freshwater through evaporation than it gains through precipitation. The remaining ten percent is contributed by river runoff. Local freshwater at the ocean surface limits exchanges of heat and moisture with the atmosphere. Surface fluxes of heat and moisture drive lower atmospheric vertical convection, horizontal advection, and precipitation patterns. Notably, surface freshwater forcing is believed to play a primary role in setting the background state and timing of the El Niño-Southern Oscillation (ENSO) phenomenon. The joint U.S./

Japan Tropical Rainfall Measuring Mission (TRMM) launched in November 1997 has begun to measure precipitation in the tropics and subtropics.

Major Scientific Questions Related to Ocean Circulation and Global Sea-Level Rise

Three areas of concern related to ocean circulation are horizontal heat transport, establishment of surface temperature patterns that control air-sea exchange, and the transport of nutrients, chemicals, and biota for biochemical processes.

Horizontal heat transport by the oceans is responsible for transporting about half of the total poleward heat flux in the global climate energy balance.

The poleward transport reaches a maximum in the Horse Latitudes (30-35° N and S), the area where western boundary currents become well formed. As an example, the British Isles are kept much warmer than Siberia in winter not by oceanic heat stored locally in the summer, but by the great northward flow of heat in the Gulf Stream.

Surface temperature patterns that are important to air-sea exchange are dominated by the need to conserve vorticity and by the mechanisms by which vorticity is generated and dissipated. Vorticity dynamics determine the position of major current systems such as the Gulf Stream, the Kuroshio, and the Antarctic circumpolar current and, thus, the related temperature patterns.

Transport of nutrients, chemicals, and biota for biochemical processes controls the productivity of the ocean and its chemical interactions with the atmosphere. Ocean models that deal with these transport phenomena are just now being developed.

Major climate-related factors that contribute to sea-level rise are thermal expansion of the oceans as well as ablating mountain glaciers and polar ice sheets. Major uncertainties exist in the contributions of the Greenland and Antarctic ice sheets to both recent and predicted future changes in sea level. Even partial shrinkage of the polar ice sheets would inundate the major coastlines of the world and produce serious economic consequences. At present the combined uncertainties in the mass balances of land ice are larger than the uncertainty in sea-level rise and contributions from other sources.

The patterns of ocean circulation are tied to patterns of sea level, but to study them with altimetric measurements of sea-surface height, the even larger tidal signal from the altimetric observations must be removed. This requires accurate tidal models which are being improved as part of the oceanographic program within EOS.

Major Scientific Questions Related to the Marine Biosphere and the Ocean Carbon System

The enormous oceanic fraction of the planetary surface accounts for the annual uptake of about 40% of the carbon dioxide emissions of mankind. The exchange of gases, and in particular carbon dioxide, between air and sea is a crucial part of the climate perturbation equation and as such is a critical area of research for the EOS program. Among questions that need to be resolved are these:

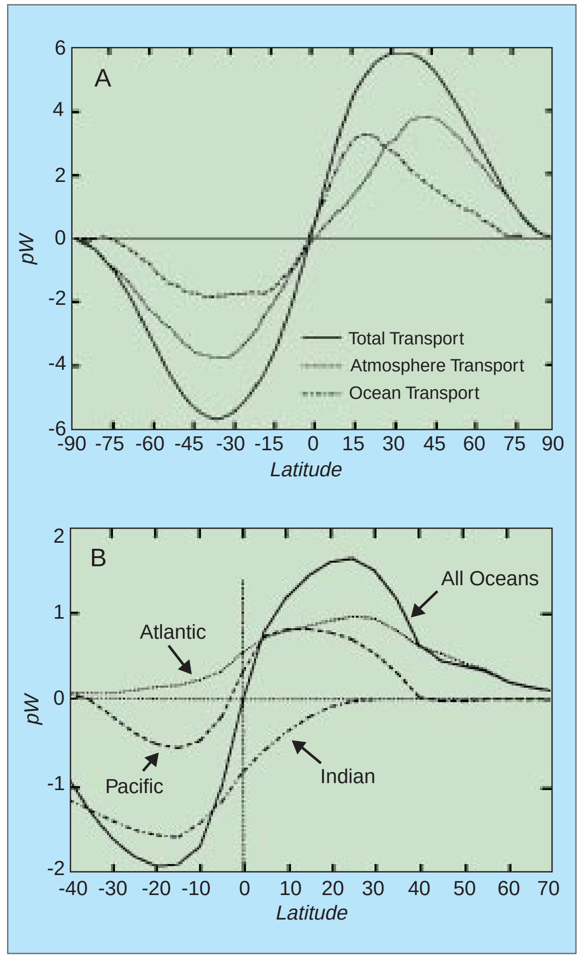
- How do changes in surface forcing of heat, momentum, and nutrient fluxes affect carbon cycling in the upper oceans?

- What are the amounts of the fluxes of carbon dioxide, carbon monoxide, and dimethyl sulfide across the air-sea interface?

- What are the factors affecting the productivity of the oceans?

Global estimates of the mean and time-varying components of ocean photosynthetic carbon production and its relation to nutrient cycles differ widely and will not be resolved without sophisticated analyses and models involving both satellite and in situ data. Large uncertainties exist in the estimates of the carbon dioxide flux across the ocean-atmosphere interface. The estimates are based on the gas-exchange flux equation, which uses an empirical proportionality parameter that suffers from considerable uncertainty. Rivers move carbon, nutrients, sediments, and freshwater to the ocean, and human activities are directly and indirectly affecting these river sources in ways that must be quantified on a global scale.

The EOS MODIS instrument will be key to the detection of the sunlight-stimulated chlorophyll *a* fluorescence signal in coastal waters, which serves as a good proxy for phytoplankton biomass and such constituents as the concentration of marine detritus.



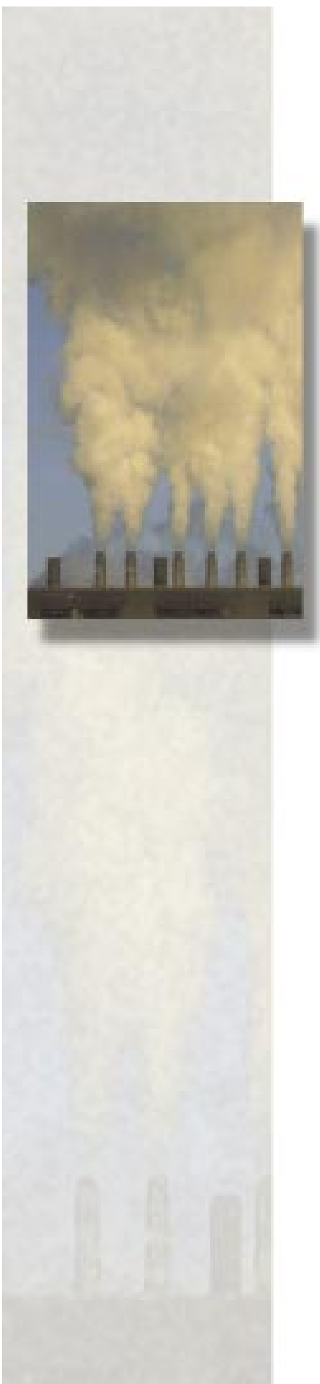
A) Estimates of the annual mean meridional energy transport (positive northward) required by the energy balance at the top of the atmosphere, estimated from atmospheric observations by Peixoto and Oort (1984) and the Earth Radiation Budget Experiment, in petawatts (=10^{15} W). The oceanic transport is obtained by subtracting the atmospheric energy transport from the total transport required by the annual energy balance.

B) Meridional profiles of the northward oceanic heat transport for the various oceans, computed indirectly from the surface heat balance *(Adapted from Hsiung, 1985).*

EOS Plans for Modeling and Observations of the Oceans

EOS interdisciplinary science investigations already well underway are using the existing knowledge base of oceanic observations to improve our knowledge of the behavior of the world oceans. These investigations will move to a new level with the advent of the improved EOS observations that will become available starting with the launch of the first EOS satellite, EOS AM-1, in 1999. The space-based observations will be augmented by many worldwide field programs as well, conducted by U.S. and international science teams.

Chapter 4
Greenhouse Gases and Atmospheric Chemistry



Introduction

Chapter 4 focuses on processes that lead to changes in the atmospheric burden of greenhouse gases and, potentially, to global climate change. These processes can be characterized as "biogeochemical" in that they involve the interaction of biological, geochemical, and photochemical processes. Thus, the questions of particular concern have to do with those processes that affect the global carbon dioxide, carbon monoxide, methane, nitrous oxide, and ozone budgets. In this chapter, six science questions are addressed; relevant EOS data products and synthetic analyses are presented; EOS algorithms, observations, and required additional data are reviewed; and the status and needs of synthesis and integrative modeling are described.

The Six Science Questions

The six questions have to do with: 1) the effect of changing land cover/land use on fluxes of greenhouse gases; 2) the effect of interannual variability in climate on biogeochemistry; 3) the effect of changing global hydrology and patterns of soil moisture on fluxes of methane and carbon dioxide in wetlands; 4) the spatial distribution and budget of tropospheric ozone; 5) the vertical distribution of tropospheric ozone; and 6) the processes that interact to control ocean carbon uptake.

Changes of land cover/land use constitute one of the most potent forces affecting global greenhouse gases. Whereas fossil fuel burning and cement production add 5.5 Gt C/yr to the atmosphere, land-cover change adds another 1-2 Gt C/yr. Land-cover changes also affect nitrous oxide and nitric oxide emissions.

Interannual variability in climate has been shown to lead to substantial interannual variability in terrestrial ecology and atmospheric chemistry. Remote sensing from satellites is the best means for understanding the geographic distribution of climate anomalies and the spatial response of the oceans and land ecosystems.

Changes in global hydrology and patterns of soil moisture in wetlands strongly affect the methane budget. New improved regional and global data sets on wetland extent and seasonality are needed.

The spatial distribution and budget of tropospheric ozone are caused by changing sources of precursors arising from fossil fuel burning, biomass burning, and, possibly, changing biogenic sources in soils and vegetation.

The vertical distribution of tropospheric ozone influences the integrated radiative effect of ozone, and, hence, its effects on climate. The vertical profile will change as the geography of sources changes, as atmospheric convection and mixing change, and as further anthropogenic sources are introduced. Accurate predictive models will be extremely difficult to develop and evaluate without strong constraints from global observations.

The processes that interact to control ocean carbon uptake are physical, chemical, and biological. The kinetics of carbon dioxide gas transfer across the ocean-atmosphere interface is slow, on the order of a year, much slower than biological processes leading to carbon uptake. What determines the partitioning of anthropogenic carbon dioxide among the atmosphere, the oceans, and the terrestrial biosphere is still the subject of research.

EOS Data Products and Analyses

Specific EOS scientific activities that relate to greenhouse gases and atmospheric chemistry can be described in terms of their contributions to the understanding of the carbon cycle, methane production and abundance, nitrous and nitric oxide production and abundance, and atmospheric chemistry and ozone.

EOS products will encompass many aspects of the carbon cycle. A global database of high-resolution analyses of land-cover change will be developed. Estimates will be made of the contribution of biomass burning to atmospheric CO_2. Trends in carbon fixation by terrestrial vegetation will be monitored in terms of changes in leaf-area index and fraction of photosynthetically-active radiation that is absorbed by vegetation. Related data of various types will be integrated into global synthetic analyses via atmospheric transport models.

Key EOS products related to methane include wetland hydrology (extent and duration of inundation) and land cover and productivity in methanogenic regions and in areas of methane oxidation.

Measurements related to nitrous and nitric oxide production and abundance will be provided by the EOS Tropospheric Emission Spectrometer (TES) instrument.

Ozone and related species will be monitored by EOS instruments, particularly those on the Chemistry 1 mission. Several instruments will measure ozone distribution directly. Measurements of Pollution in the Troposphere (MOPITT) will make measurements of carbon monoxide and methane. Moderate-Resolution Imaging Spectroradiometer (MODIS) observations of fire will lead to estimates of biomass burning contributions of hydrocarbons, methane, oxides of nitrogen, and nonmethane hydrocarbons to ozone production.

Figure A shows how EOS data and models can be integrated to model the carbon cycle. The ocean, ecosystem, and land-use-change fluxes are combined to produce spatial maps of terrestrial sources and sinks of CO_2, with fossil and cement sources also included from statistical data.

Figure B shows how trace gases and the ozone cycle may be modeled. Fluxes of nitrogen- and carbon-based gases are derived from surface observations and then used as inputs to atmospheric chemical transport models. Direct retrievals of the distributions of greenhouse gases from TES, MOPITT, and High-Resolution Dynamics Limb Sounder (HIRDLS) and other EOS instruments can also be passed to the chemical transport models. Other information about anthropogenic gases from various sectors of the economies of the world can also be passed to the chemical transport models.

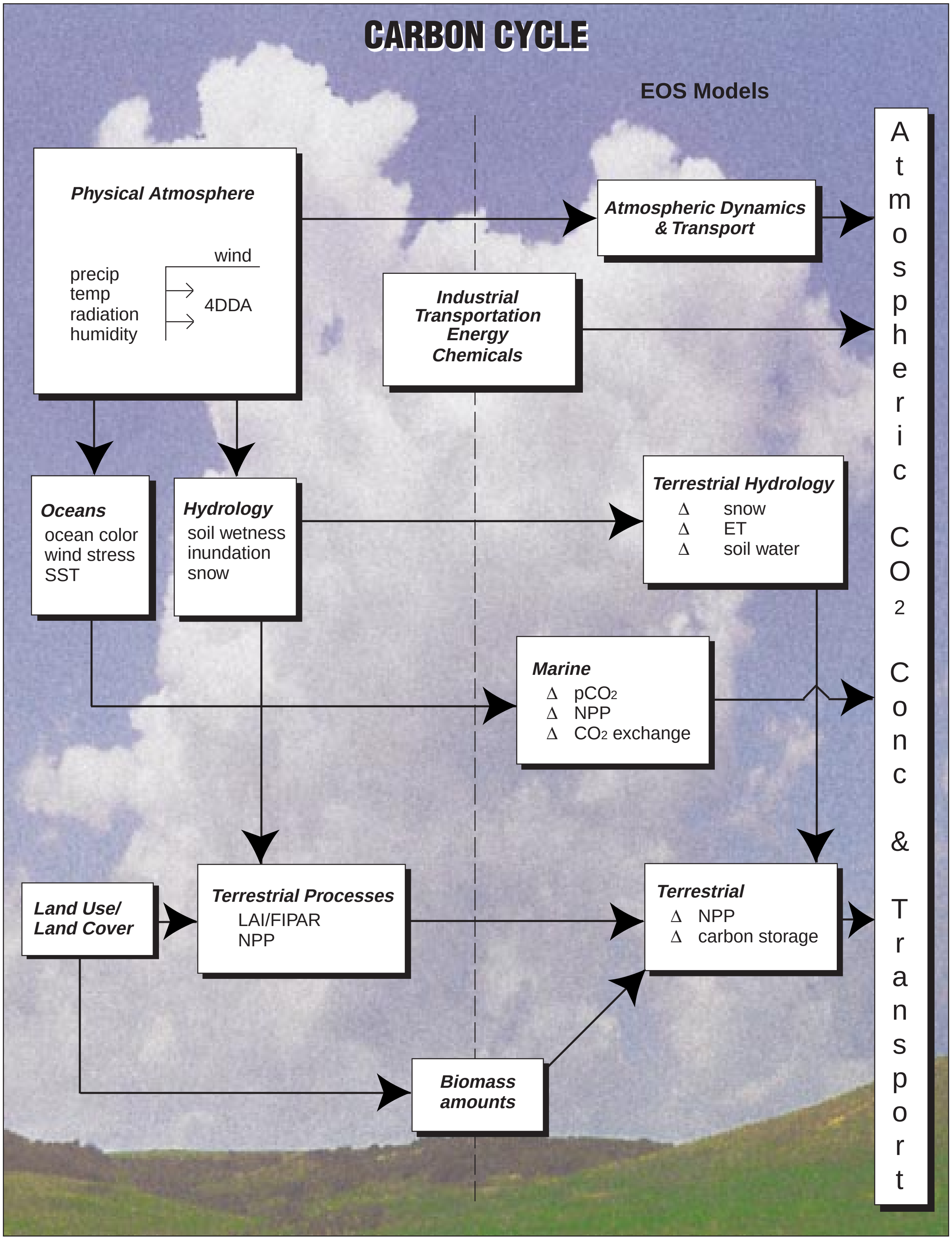

CARBON CYCLE
EOS Models
Physical Atmosphere
precip
temp
radiation
humidity
wind
4DDA
Atmospheric Dynamics & Transport
Industrial
Transportation
Energy
Chemicals
Oceans
ocean color
wind stress
SST
Hydrology
soil wetness
inundation
snow
Terrestrial Hydrology
Δ snow
Δ ET
Δ soil water
Marine
Δ pCO_2
Δ NPP
Δ CO_2 exchange
Land Use/ Land Cover
Terrestrial Processes
LAI/FIPAR
NPP
Terrestrial
Δ NPP
Δ carbon storage
Biomass amounts
Atmospheric CO_2 Conc & Transport

Figure A

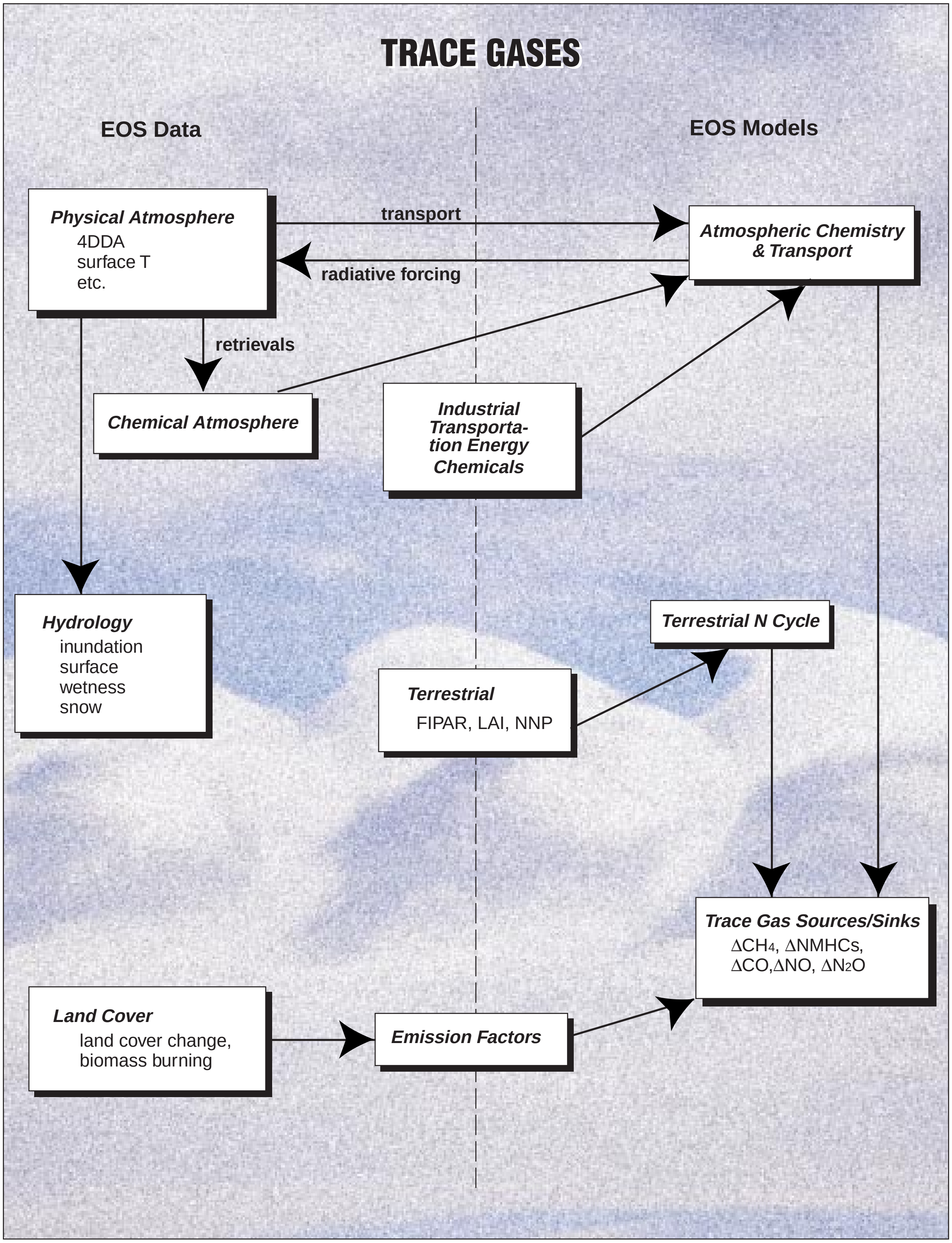

TRACE GASES
EOS Data
EOS Models
Physical Atmosphere
4DDA
surface T
etc.
transport
radiative forcing
Atmospheric Chemistry & Transport
retrievals
Chemical Atmosphere
Industrial Transporta-tion Energy Chemicals
Hydrology
inundation
surface
wetness
snow
Terrestrial N Cycle
Terrestrial
FIPAR, LAI, NNP
Trace Gas Sources/Sinks
ΔCH_4, ΔNMHCs,
ΔCO, ΔNO, ΔN_2O
Land Cover
land cover change,
biomass burning
Emission Factors

Figure B

Chapter 5
Land Ecosystems and Hydrology

Introduction

Chapter 5 focuses on the role of the land system in the three areas of land-climate, land-hydrology, and land-vegetation interactions. Fluxes of CO_2 and other greenhouse gases from the land surface influence the global circulation directly. Changes in land cover lead to changes in the land-surface biophysical properties of energy and mass exchange and also affect surface hydrologic balances. Finally, both climate and hydrology changes jointly control biospheric productivity, the source of food, fuel, and fiber for humankind. The EOS program provides satellite-based remote-sensing instruments that can quantify the spatial and temporal variability of the land-surface attributes that are critical to understanding these complex interactions.

The primary concern regarding land-climate interactions is to learn how changes in land-surface processes and properties interact with, and cause changes in, both regional and global climate. Land-surface properties such as type of cover, leaf-area index, roughness length, and albedo must be determined and made available to land surface parameterization (LSP) schemes, which are then coupled to Atmospheric General Circulation Models (AGCMs). These models are then used interactively to predict climate change and also changes in land-surface properties such as characteristics of vegetation that are related to climate change.

The primary concern regarding land-hydrology interactions is with changing climate and land-surface characteristics that may combine to change precipitation patterns, surface-water partitioning and storage, and river flows. Of further concern is the land processes that may alter water quality: erosion, sedimentation, and river biogeochemistry.

The primary concern regarding land-vegetation interactions is with how biome distribution is influenced by, and in turn influences, changes in land cover and climate. There are serious questions relating to how the regional distribution and magnitude of crop, range, and forest productivity will change with climate and land-use change.

Major land-surface science issues can be treated in terms of the three aspects of land-climate, land-hydrology, and land vegetation.

Land-Climate Science Issues

Many land-climate science issues are addressed in this chapter of the EOS Science Plan. The current generation of AGCMs that is being used to study climate contains representations of land and ocean surface interactions with the atmosphere. A new generation of land-surface models (LSMs) has been developed to work with the

AGCMs. The LSMs generally contain formulations that model surface radiation fluxes, turbulent and mass fluxes, liquid water fluxes, and control of water vapor and CO_2 fluxes by vegetation. Various LSMs still exhibit major differences in their predictions of change. Current models still do not do a good job of representing water and energy exchanges between the land and the atmosphere that must be known in order to predict correctly the temporal and spatial fields of precipitation and surface radiation.

There are questions regarding possible highly complicated interactions and feedbacks between the atmosphere and the surface wherein elevated levels of atmospheric CO_2 may cause changes in the biosphere. It has been found that realistic representations of land-surface cover and moisture characteristics are likely to lead to greatly improved weather forecasting skill.

Land-Hydrology Science Issues

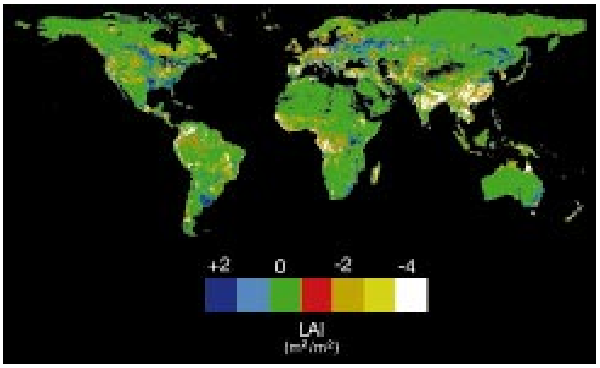
Many land-hydrology phenomena must be addressed at smaller scales than are commonly employed in general circulation models (GCMs) and other climate modeling representations. The challenge to EOS scientists is to strive to improve hydrologic understanding at these critical human scales. Thus key science issues for land-hydrology are: 1) to identify and quantify key hydrologic variables across a range of scales and 2) to develop or modify hydrologic process models to take advantage of operational and realistic data sources.

The extensive list of hydrologic variables that require more study includes precipitation, runoff, evapotranspiration, near-surface soil moisture, infiltration and deep percolation, radiation, and near-surface meteorology. Information is also needed for the estimation of the land-surface water balance and the estimation of the possibilities for extreme hydrologic events such as severe storms, floods, and droughts. The role of river biogeochemistry in affecting water quality and the functioning of aquatic ecosystems must also be examined.

Vegetation Science Issues

EOS vegetation science issues encompass regional-to-global scales, from the carbon balance of the boreal forest to biospheric net primary production. Because of the short time scale of vegetation responses to climate, EOS measurements will range from following interannual variability in spring phenology to seasonal changes in daily terrestrial surface CO_2 balance to annual and interannual changes in net primary production (NPP).

Direct measurements from EOS will include aspects of land cover and land-cover change. Other biophysical variables such as leaf-area index, fraction of photosynthetically-active radiation that is absorbed, albedo, and vegetation indices are derived from direct measurements. A key derived product is NPP, and the EOS Moderate-Resolution Imaging Spectroradiometer (MODIS) instrument was specifically designed, in part, to calculate this parameter. MODIS will produce values of NPP on a weekly basis to be available globally at 1-km resolution.



Human-induced changes in global land cover estimated by comparing AVHRR NDVI data, expressed as leaf-area index, with potential leaf index computed from long-term climatological data and hydrologic-vegetation equilibrium theory *(Nemani et al., 1996).*

Related EOS Science Measurements

Among the suite of EOS instruments to be flown starting in 1998, four instruments will be playing key roles in providing data about the Earth's surface characteristics. These instruments are the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Enhanced Thematic Mapper + (ETM+), Multi-Angle Imaging Spectroradiometer (MISR), and MODIS.

ASTER, operating in the visible, shortwave infrared, and thermal infrared, will provide surface reflectances and radiative (brightness) temperatures with 15-to-30-m resolution. The thermal infrared radiances can be used to derive surface kinetic temperatures and spectral emissivities. The kinetic temperatures can then be used to determine sensible and latent heat fluxes and ground heat conduction. Still other parameters can be derived from the surface kinetic temperatures as well.

ETM+ on the Landsat-7 platform, operating in the visible, near and shortwave infrared, and thermal infrared, will be used primarily to characterize and monitor changes in land cover and land-surface processes. It will have a panchromatic band with 15-m resolution, and will have 30-m resolution in the visible and infrared channels, except for 60-m resolution in the thermal infrared. The characteristics of ETM+ are such that it will provide data sufficiently consistent with previous Landsat data to meet requirements for global-change research.

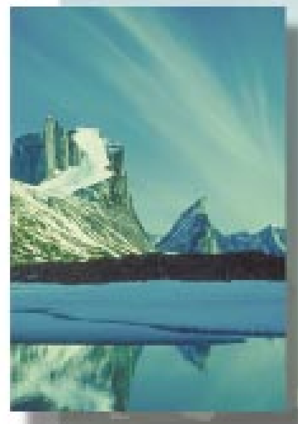
MISR, operating in the visible, and viewing the Earth at nine discrete angles, will provide measurements that lead to determination of surface albedo and vegetation canopy structural parameters, thereby leading to derivations of photosynthetically-active radiation and improved values of canopy photosynthesis and transpiration rates.

MODIS, operating in the visible and infrared with spatial resolution from 250 m to 1 km at nadir, will be the primary sensor for providing data on terrestrial biospheric dynamics and vegetation process activity. Land products from MODIS include spectral albedo, land cover, spectral vegetation indices, snow and ice cover, and surface temperature and fire, plus biophysical variables such as leaf-area index and fractional photosynthetically-active radiation.

Chapter 6
Cryospheric Systems

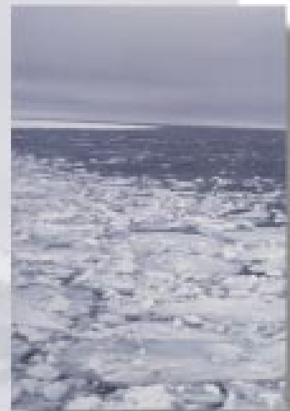
Introduction

Chapter 6 focuses on those portions of the Earth's surface where water is in a solid form and includes all these elements: sea ice, lake ice, river ice, snow cover, glaciers, ice caps and ice sheets, and frozen ground (which includes permafrost). As an integral part of the global climate system the cryosphere has important linkages and feedbacks with the other elements of the system such as surface energy and moisture fluxes, clouds, precipitation, hydrology, and atmospheric and oceanic circulation. Knowledge of the many elements of the cryosphere is essential to the correct modeling of climate and predictions of global change.



At a time of general concern with the possibility of human-induced global warming there is a particular concern with the possibility of associated melting ice sheets and the consequent rise in sea level that may ensue. In addition to the possible flooding of coastal areas and low-level oceanic islands due to sea-level rise, there is also the possibility of adverse effects on water supply and navigability of waterways. Accurate information on the rate and magnitude of changes in the cryospheric elements is essential for policy and decision making, particularly over the high latitudes of the Northern Hemisphere, where climate warming is projected to be the greatest.

The importance of the cryosphere in climate studies is clearly reflected in the Earth Observing System (EOS) program. EOS now incorporates a dedicated snow-and-ice Distributed Active Archive Center (DAAC), a specific satellite mission (Ice, Clouds, and Land Elevation Satellite [ICESat]) dedicated to ice-sheet altimetry, and a considerable number of interdisciplinary science investigations (IDS) undertaking research to improve understanding and modeling of cryospheric processes, cryospheric variability, and cryosphere-climate interactions. In addition to the altimetry measurements to be provided by the Geoscience Laser Altimeter System (GLAS) on the ICESat spacecraft, other EOS instruments such as the Moderate-Resolution Imaging Spectroradiometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), operating in the visible- and infrared-wavelength regions will be providing surface temperature and reflectivity measurements and snow-cover distribution, and the Advanced Microwave Scanning Radiometer-EOS Version (AMSR-E) instrument, operating in the microwave region, will make complementary determinations of snow cover and sea-ice characteristics and distribution.



Background

The majority of the world's ice volume is in Antarctica, principally in the East Antarctic Ice Sheet, but winter snow and ice in the Northern Hemisphere have the largest area. The most important physical properties of snow and ice that modulate energy exchanges between the surface and the atmosphere are surface reflectance, thermal diffusivity, and latent heat. Thermal diffusivity is a measure of the ability to transfer heat, and latent heat is a measure of the ability to change state. Surface roughness, emissivity, and dielectric characteristics contribute importantly to making observations of snow and ice from space.

Snow cover has the largest areal extent of any component of the cryosphere, with a mean maximum areal extent of approximately 47 million km^2, most of it located in the Northern Hemisphere. A close relationship between hemispheric air temperature and snow cover has been observed during the satellite-observation years. This has led to considerable interest in monitoring Northern Hemisphere snow-cover extent for detecting and monitoring climate change. Interestingly, the control of shortwave energy exchange by snow cover affects the availability of photosynthetically-active radiation (PAR) needed for the productivity of sub-ice algae.

Sea ice covers much of the polar oceans, and satellite data have shown considerable seasonal, regional, and interannual variability in the sea-ice covers of both hemispheres. The passive microwave record from late October 1978 through the end of 1996 shows that the extent of Arctic sea ice has been decreasing at a rate of 2.9% per decade, while the extent of Antarctic sea ice increased by 1.3% per decade. Both "leads" and polynyas are very important components of the sea-ice regime, playing a dominant role in exchanges of heat and moisture to the atmosphere during the polar winter. Polynyas also have an important role in primary productivity, allowing significant absorption of PAR within the water column.

Lake ice and river ice evince considerable variability in their dates of appearance and disappearance. The sizes of the ice bodies are too small to exert other than localized climatic effects. Still, observations of lake ice can serve as a useful proxy climate record. River-ice observations are less useful as a climatic proxy record because river-ice formation is strongly dependent on a river-flow regime that is affected by many other factors. Accordingly, there is no river-ice research component in EOS. The appearance and disappearance of lake ice are readily observed in the visible, and microwave sensors are well suited to monitoring important lake-ice characteristics such as freeze-up, break-up, freeze-to-bottom, and surface-melt onset. Freeze-up and break-up correlate well with air temperature or freezing-degree days.

Permafrost is perennially frozen ground and may occur where mean annual air temperatures are less than -1 or -2° C. It underlies approximately 20% of Northern Hemisphere land areas, with thicknesses exceeding 600 m along the Arctic coast of northeastern Siberia and Alaska. Permafrost may form under present-day polar climates where glaciers retreat or land emergence exposes unfrozen ground.

Ice sheets are the greatest potential source of global freshwater, holding approximately 77% of the global total. This corresponds to 80 m of world sea-level equivalent, with Antarctica accounting for 90% of this and Greenland accounting for most of the remaining 10%. Climatic perturbations produce only slow variations in ice sheets, occurring over glacial and interglacial periods. Valley glaciers, on the other hand, respond rapidly to climatic fluctuations, with typical response times of 10-50 years. While glacier variations are likely to have minimal effects on global climate, their recession may have contributed one third, to one half of the observed 20th-century rise in sea level. The mass balance of land-based glaciers and ice sheets is determined by the accumulation of snow, mostly in winter, and warm-season ablation due primarily to net radiation and turbulent heat fluxes to melting ice and snow from warm-air advection. Satellites are playing an increasingly important role in furthering understanding of the Greenland ice-sheet mass balance by providing accurate surface-elevation data, ice-flow velocity, and surface ablation information.

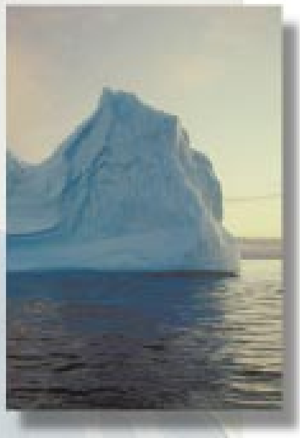
Major Scientific Questions Related to Cryospheric Science

Three areas of concern related to cryospheric science are: 1) representation of cryospheric processes in climate and hydrological models; 2) cryosphere-climate linkages and feedbacks; and 3) cryospheric variability and change.

Representation of Cryospheric Processes in Climate and Hydrological Models

Recent studies have shown that atmospheric general climate models (GCMs) suffer from inadequate treatment of sea-ice processes involving snow albedo, heat storage, and conduction. Lack of vegetative masking of snow albedo in some models has led to a significant cold bias in spring air temperatures over northern Eurasia. Year-round calculations of snow cover have a strong effect on the calculations of runoff. All of the following processes must be properly represented in models in order to provide realistic simulations of the snowpack: snow metamorphism (or aging), resolution of vertical gradients, and snow-rain separation. There is a general lack of suitable evaluation data to assess the performance of snowpack models. EOS products from MODIS, such as surface temperature, albedo, and snow cover and EOS products from AMSR-E, such as snow-water equivalent and depth, will be of great assistance here. While there is as yet no widely suitable method to directly map snow-cover equivalence in rugged mountains, higher resolution snow products from EOS will help to address this issue. There is still the need for multi-polarized synthetic aperture radar (SAR) to make reliable estimates of snow-water equivalence in alpine areas.

Sea-ice dynamics—advection and deformation—must be included in climate models to account for the freshwater provided by melting sea ice advected from the Arctic into the Greenland and Norwegian Seas and to reproduce dynamic/thermodynamic feedback effects involving open-water "leads". Also, sea-ice changes have a major impact on the availability of moisture and the mass balance of major ice sheets, especially Antarctica. Recent studies have shown that relatively modest changes in thermodynamic parameterizations of sea ice may have a disproportionate effect on simulated ice-thickness variability and thereby have a major impact on simulated climate variability.



Lake-ice neglect in GCMs has led to incorrect simulation of the seasonal cycle of discharge from the Mackenzie River and to an incorrect supply of freshwater to the Arctic Ocean in coupled models.

Permafrost restricts moisture exchanges between surface water and deep ground water and is therefore an important factor in controlling drainage and the areal and spatial distribution of wetlands. Accurate simulation of permafrost processes such as active-layer development will require modeling schemes with additional soil layers and better understanding of heat and water flow in organic soils. The inclusion of frozen soil in hydrological models is a major objective of the Canadian Global Energy and Water Cycle Experiment (GEWEX) program.

Glaciers and ice sheets need improved representation in climate models and in hydrological models as well. There are major uncertainties regarding the future behavior of the great ice sheets, and there are major knowledge gaps that need to be filled in order for climate models to provide better estimates of glacier and ice-sheet mass balance and their contributions to sea-level change. Among the knowledge gaps are the linkage of meteorology to mass balance and dynamic response, the need for research on a broader spectrum of glacier environments, quantification of the process of meltwater refreezing, and increased understanding of the process of iceberg calving.

Runoff is one of the major links between glaciers and ice sheets and the global climate system, and runoff is crucially important from a water-resources perspective. Glacier and ice-sheet runoff are also important from an ecological perspective, affecting habitat sustainability and wildlife management through influences on stream-water turbidity and temperature.

Representation of Cryosphere-Climate Linkages and Feedbacks

Cryosphere-climate feedbacks can be classified into the main categories of feedbacks working through the freshwater cycle and feedbacks working through the surface-energy balance. The freshwater cycle is intimately connected to the cryosphere through the storage and transport of freshwater in solid form. The storage and transport occur over a wide range of time scales and, therefore, are involved in climate variability over a similar range of time scales. On short time scales (seasonal and annual) the accumulation and melting of snow dominates the hydrological cycle of many alpine and high-latitude drainage basins. On annual-to-decadal time scales sea ice can store freshwater and transport it from one region to another, as ice drifts under the influence of winds and currents. In the Northern Hemisphere ice melts as it is transported out of the Arctic into the North Atlantic, thus forming a stabilizing freshwater layer at the surface. The freshwater layer may moderate deep convection in the North Atlantic and thereby affect the global "conveyor belt" circulation, which is important for transporting oceanic heat northward and sequestering carbon dioxide in the deep ocean. On still-longer time scales, melting of large glaciers and ice sheets can lead to substantial raising of global sea level.

The surface-energy balance over both land and ocean can be modified as a result of the cryosphere's interaction with the climate system. The two principal mechanisms involving ice and snow cover are insulation of land and ocean surfaces from the atmosphere, or feedback with outgoing longwave radiation (OLR), and enhancement of the surface albedo, or shortwave feedback. The shortwave feedback is the classic feedback between temperature and albedo wherein higher air temperatures melt ice and snow and thereby decrease albedo, leading to greater absorbed energy and warmer temperatures.

Data sets required to develop and validate parameterizations of the surface-energy-exchange process *(WCRP, 1997).*

Parameter Name	Units	Accuracy Need/Avail or Absolute::Rel	Temporal Resolution	Spatial Resolution or Horizontal Resolution::Cover	Vertical Resolution	Source
Sea-ice concentration	%	7%	daily	20 km	—	AMSR-E
Floe-size statistics	—	10%	weekly	100 km	—	MODIS, Radarsat
Ridge statistics	—	10%	weekly	100 km	—	Radarsat
Cloud fraction	—	4% / 30%	daily	1 km	—	MODIS, climatology, stations
Cloud optical depth	—	15%	daily	1 km	—	MODIS, aircraft
Cloud particle phase	—	—	daily	1 km	—	MODIS, aircraft
Cloud effective particle radius	—	25%	daily	1 km	—	MODIS, aircraft
Cloud top temperature	—	6%	daily	1 km, 100 km	—	AIRS, AMSU, MODIS
Cloud top pressure	—	6%	daily	100 km	—	AIRS, AMSU, HSB
Atmos. ice crystal precip.	—	—	—	—	—	ICESat, aircraft
Atmospheric aerosol	—	—	—	—	—	ICESat, aircraft
Surface albedo	—	0.05 / 0.1	daily	1km	—	MODIS, climatology
Ice surface	—	1 K / 2 K	daily	1 km, 100 km	—	MODIS, AIRS, buoys, stations
Surface roughness	—	—	—	—	—	laser, survey
Humidity profile	g/kg	10% (goal)::5%	2/day (d, n)	50 × 50 km::G	2 km::Atmos	AIRS (05), HSB
Temperature profile	K	1.0 K::0.4 K	2/day (d, n)	50 × 50 km::G	2 km::Atmos	AIRS (07)

Representation of Cryospheric Variability and Change

To be adequate, a good representation of cryospheric variability and change must account for variability in snow, sea ice, lake ice, frozen ground and permafrost, and glaciers and ice sheets.

The existing satellite snow databases are currently too short to provide information on the natural variability in continental-scale snow cover needed for climate-change detection and for validating transient simulations used in global climate models. Still, two important databases are available for assistance with this problem. The weekly National Oceanic and Atmospheric Administration (NOAA) visible satellite-based snow-cover analysis dates back to 1972, and there are Scanning Multispectral Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I) passive microwave data from 1978, which can be used to derive snow extent, snow depth, and snow-water equivalence. It is interesting that the rapid decrease in Northern Hemisphere spring snow-covered area that characterized the 1980s appears to have reversed itself during the 1990s.

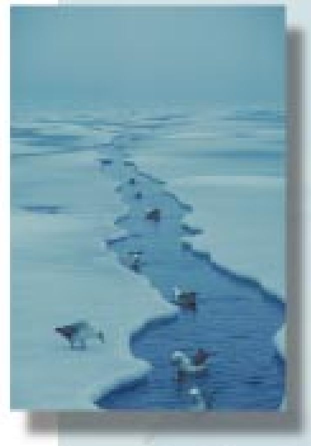
Determining the mass or volume of sea ice requires measurements of both areal coverage and thickness. The AMSR-E will be the EOS instrument that will continue the satellite record of sea-ice concentration and extent, but so far there is no direct satellite method to measure ice thickness. (A system is being developed to use SAR along with kinematic histories of sea ice to derive ice thickness.)

Data sets and accuracy required to monitor glacier and ice-sheet responses to changing climate *(WCRP, 1997).*

Parameter Name	Units	Accuracy Needed/Available	Temporal Resolution	Spatial Resolution	Vertical Resolution	Source
Ice surface topography	m	0.5 - 5 m /?	yearly	10 - 100 m	1 - 10 m	ICESat, SAR
Area covered by ice	km^2	0.01 - 0.5 km^{-2} /0.001 km^{-2}	yearly	100 m - 1 km	—	ASTER, AVHRR, ETM, MODIS, TM
Ice-thickness distribution	m	0.5 - 5 m /?	yearly	100 m - 1 km	1 - 10 m	SAR
Ice-flow velocity	m d^{-1}	0.05 - 0.5 m d^{-1} /?	daily, yearly	0.1 - 1 m	—	ICESat, SAR
Seasonal ice/ snow cover	km^2	0.01 - 0.5 km^{-2} /0.001 km^{-2}	daily, yearly	10 m - 1 km	—	ASTER, AVHRR, ETM, MODIS, TM
Snow-depth distribution	m	- 0.25 m	daily, yearly	10 m - 1 km	0.05 - 0.5 m	ASTER, SSM/I
Snow-water equivalent	mm	2.5 - 25 mm	daily	10 m	5 - 50 mm	SAR
Surface temperature	K	0.5 K / 2 K	daily	10 m - 1 km	—	ASTER, AVHRR, ETM, MODIS, TM
Albedo distribution	%	1% /5-10%	daily	10 m - 1 km	—	ASTER, AVHRR, ETM, MODIS, TM,
cloud cover	%	10%	daily	1 - 10 km	—	CERES
Meltwater runoff	Yes /No	— /—	daily	1 - 100 m	—	ASTER, TM, ETM

Satellite observations of lake-ice freeze-up/break-up are particularly valuable for validating/calibrating physical lake-ice models. Satellites operating in the visible and both passive and active microwave regions can all provide useful information.

Satellites, through their global coverage, are ideally suited for monitoring the vast, uninhabited areas underlain by permafrost. Unfortunately, permafrost being a sub-surface feature, cannot be observed directly from space so that extent and change have had to be indirectly deduced from related micro-climate and surface vegetation characteristics that can be detected by remote-sensing techniques. Recent work has shown that it is possible to use multidimensional SAR configurations together with optical sensors to map frozen ground and associated features.



EOS promises to make great advances in determining glacier and ice-sheet responses to climate change. Surface-area determinations and differentiation into cover classes have been achieved using Thematic Mapper (TM) and Advanced Very High-Resolution Radiometer (AVHRR) data for the Greenland ice sheet. SAR data may be useful for the determination of the ice-thickness distribution, and data from SAR and GLAS may help to determine small changes in surface elevations.

Required Measurements, Data Sets, and Parameterizations

The table on page 39 (for parameterizations of the surface-energy-exchange process) is presented here as an example of the measurements that will be made by elements of EOS. This example shows the use of the AIRS/AMSU/HSB, AMSR-E, GLAS, and MODIS instruments along with instrumented aircraft, buoys, and ocean stations.

As another example, the table on page 34 shows the roles of ASTER, AVHRR, CERES, ETM, GLAS, MODIS, SAR, SSM/I, and TM (on Landsat) in contributing to monitoring glacier and ice-sheet responses to changing climate.

Chapter 7
Ozone and Stratospheric Chemistry

Introduction

Chapter 7 focuses on stratospheric ozone, its role in climate change, and the natural and anthropogenic causes of changes in it. Stratospheric ozone shields the Earth's surface from solar ultraviolet radiation. Stratospheric ozone also plays an essential role in setting the temperature structure and therefore the radiative heating/cooling balance in the atmosphere, especially in the stratosphere.

Four major sections of the chapter give: first, a general background of what is known about stratospheric ozone, second, a review of major scientific issues, third, a description of required measurements and data sets, and fourth, the anticipated EOS contribution to the fund of knowledge and understanding of stratospheric ozone.

Background Information

Ozone changes can affect climate, in the sense that removal of ozone from the stratosphere would cause cooling of the stratosphere and beyond that a small, but non-negligible, offset to the greenhouse forcing from CO_2, N_2O, CH_4, CFCs, etc. The size of the radiative forcing due to stratospheric ozone loss is very sensitive to the profile shape assumed for that loss.

What might be called normal ozone changes have been observed on various time scales, including seasonal and interannual. Seasonal changes are basically determined by the winter-summer changes in the stratospheric circulation. Interseasonal changes are linked to the eleven-year solar cycle in UV input from the sun and to the amount of volcanic aerosols in the stratosphere. Superimposed on the natural changes are anthropogenic changes largely related to the release into the atmosphere of human-made chemicals containing chlorine.

The most significant departure from the natural ozone distribution has been the change in Antarctic polar ozone, leading to the phenomenon known as the ozone hole. Not until 1996 have changes in Arctic polar ozone been detected that are in any way comparable to the changes in the Antarctic polar ozone. In recent decades it has become clear that there are also small but statistically significant decreases in midlatitude stratospheric ozone as well.

Changes in stratospheric ozone distribution can be understood in terms of chemical processes, transport, interactions with aerosols and polar stratospheric clouds, and interactions with solar ultraviolet radiation and energetic particles.

The basic outline of the chemical processes that control stratospheric ozone appears to have been established. Principal ozone destruction processes have to do with catalytic reactions involving hydrogen, nitrogen, chlorine, and bromine radicals. The source gases for the halogen radicals—the chlorofluorocarbons (CFCs) and bromocarbons—are principally anthropogenic. The amount of the radicals can be strongly affected by reactions on the surface of stratospheric aerosols and even more profoundly affected in the polar winter by reactions on the surface of polar stratospheric clouds (PSCs).

The annual cycle of total ozone is largely driven by transport effects. For example, large-scale waves present in the winter stratosphere have the effect of building up ozone levels in the higher winter latitudes.

Clearly, variability in ultraviolet radiation reaching the Earth leads to changes in global total ozone. For example, from 1986 to 1990 the solar UV increased with the onset of the 11-year solar cycle and resulted in an increase of global total ozone of almost 2%. Energetic particle flux from the sun may also drive natural ozone variations in the mesosphere and upper stratosphere.

Both two-dimensional (2D) and three-dimensional (3D) models are used by several research groups for studies of ozone behavior. Although these models give reasonable agreements with many aspects of ozone measurements, they are still lacking in some important respects. For instance, the 2D models have not been able to provide accurate representations of the ozone trends that were observed in middle and high latitudes over the 1980-1990 time period. The 3D models suffer from unrealistic temperature fields which, in turn, alter the photochemistry.

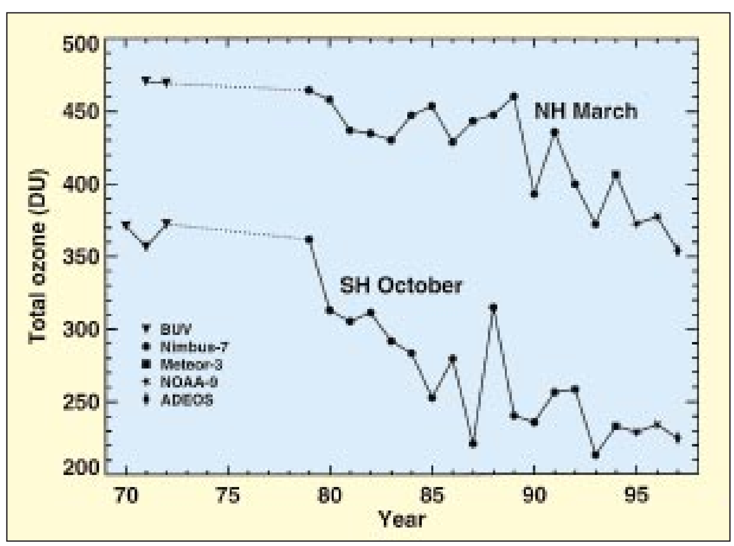
Major Scientific Issues

The major scientific issues in regard to our understanding of ozone phenomena are divided into natural changes and human-made changes. Separating these components is the goal of much ozone and trace gas research.

The natural changes to be dealt with have been cited before. They include the interannual and long-term variability of the stratospheric circulation; the changes in external influences such as solar and energetic particles; and changes in natural aerosols by volcanic eruptions and changes in PSC amounts due to interannual variations in polar stratospheric temperatures

Human-made changes are principally those associated with the release into the atmosphere of unreactive chlorine- and bromine-containing compounds such as the CFCs. Aviation also has an impact on ozone through the release of nitrogen radicals in aircraft exhaust.

63°-90° total ozone average



Required Measurements and Data Sets

The minimum measurement requirements, and the EOS instruments which will make the measurements, are shown in the table. Often key measurements are to be made by more than one instrument giving the whole measurement suite a desirable level of robustness in case of instrument failure.

Required measurements must satisfy the need for meteorological information; the need for chemical information including both chemical and dynamical measurements in both the stratosphere and troposphere; the need for stratospheric aerosol and PSC information; and the need for solar-ultraviolet flux determinations. In addition, there must be a concerted effort at validating the satellite measurements.

EOS Contributions

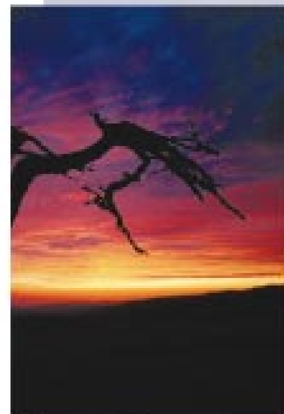
There are many potential EOS contributions to the understanding of changes in stratospheric ozone. The contributions will be in meteorological measurements, chemical measurements, aerosols, solar ultraviolet flux, and advanced modeling techniques. Just a few of the improvements are mentioned here.

Stratospheric chemical and dynamical measurement requirements. Requirements include vertical resolution of 1-2 km through the tropopause into the lower stratosphere. Horizontal resolution is minimally that of UARS (2700 km), but increased horizontal resolution vastly improves the science. HIRDLS scanning will achieve a horizontal resolution of 400 km. AMLS may achieve a horizontal resolution of 100 km with MMIC array technology.

▼

Measurement	Accuracy	EOS Instrument
Meteorology		
Temperature	1K	MLS, HIRDLS, SAGE III
Winds	2-5 m/s	(none)
Chemistry		
O_3	0.2 ppm	MLS, HIRDLS, SAGE III
H_2O	0.5 ppm	MLS, HIRDLS, SAGE III
CFC-11 / 12	0.2 ppb	HIRDLS
N_2O	20 ppb	MLS, HIRDLS
CH_4	0.1 ppm	HIRDLS
HCl	0.1 ppb	MLS
$C1ONO_2$	0.1 ppb	HIRDLS
HNO_3	1.0 ppb	HIRDLS, MLS
NO_2 / NO	0.2 ppb	HIRDLS, SAGE III
C1O	50 ppt	MLS
BrO	5 ppt	MLS
OH	0.5 ppt	MLS
N_2O_5	0.2 ppb	HIRDLS
Aerosols	Surface area within 10%	SAGE III, HIRDLS
Solar Flux	100-400 nm to 4%	SOLSTICE

EOS limb sounders (Microwave Limb Sounder [MLS] and High-Resolution Dynamics Limb Sounder [HIRDLS]) will greatly improve the accuracy, precision, and resolution of temperature measurements in the tropopause region. HIRDLS will provide higher horizontal resolution temperature profiles than have been available heretofore. MLS will provide hydroxyl (OH) measurements that were not previously available. The Stratospheric Aerosol and Gas Experiment III (SAGE III) instrument will provide many advances, including the first satellite measurements of the size distribution of PSCs. Fully interactive chemical dynamical models are being developed especially for interpretation of EOS data. Wind fields provided by the NASA/GSFC Data Assimilation Office are of sufficient quality to remove the dynamical uncertainty from tracer observations.



Chapter 8
Volcanoes and Climate Effects of Aerosols

Introduction

Chapter 8 focuses on volcanoes, volcanic eruptions that inject gases and particles into the atmosphere, the conversion of volcanic gases into aerosols, and on stratospheric and tropospheric aerosols more generally as they interact with climate. Major sections of this chapter discuss: explosive volcanic eruptions and how they may lead to stratospheric aerosols that have climatic effects, and tropospheric aerosols, their sources, and their important climatic effects. A brief review is included of other types of volcanic hazards, hazard prevention, preparedness, and relief measures. A second section treats the measurements and data sets that are required to improve understanding of the impacts of stratospheric and tropospheric aerosols. A final section sets forth the anticipated EOS contributions to scientific knowledge and the national benefit to be derived from the volcanology and aerosol research performed as parts of EOS.

Background Information

Volcanic emissions can cause significant variations of climate on a variety of time scales—just one very large eruption can cause a measurable change in the Earth's climate with a time scale of a few years. Sulfur dioxide released from the magma may be oxidized to sulfuric acid aerosols in the stratosphere, which may reside there for a year or more, generally producing cooling at the Earth's surface. In performing research on global change it is important to distinguish climate effects of natural phenomena such as volcanic aerosols from those effects due to human activities.

Stratospheric aerosols produced by volcanic eruptions can influence stratospheric chemistry both through chemical reactions that take place on the surface of the aerosols and through temperature changes induced by their presence in the stratosphere.

A wide variety of aerosol types is found in the troposphere, including sea salt and dust carried from the surface into the atmosphere by winds, and aerosols formed by chemical transformations from gaseous to liquid or solid forms. Volcanic eruptions can also contribute to tropospheric aerosols, and there are other natural sources including biogenic particles and products from natural fires. Aerosols contributed by humans have been increasing, particularly those associated with SO_2 from combustion of fossil fuels and from biomass burning. The primary effect of these anthropogenic aerosols on the Earth's energy balance is a cooling of about -0.5 Wm^{-2} compared to the forcing associated with the change in greenhouse gases during the industrial age of about +2 Wm^{-2}. Subsonic aircraft flying in the lower stratosphere are also a source of aerosol particles.

Accurate measurements of aerosols are also needed to provide corrections for remote sensing of Earth surface properties.

Major Scientific Questions and Hypotheses

Major scientific questions to be dealt with at this time have to do with: stratospheric volcanic aerosols and their effect on climate, the "sulfur budget" of individual eruptions, which defines the percentage of gas dissolved in the melt that is released in the eruption, the role of volcanic aerosols in ozone depletion, tropospheric aerosols and their effect on climate, and volcanic hazards.

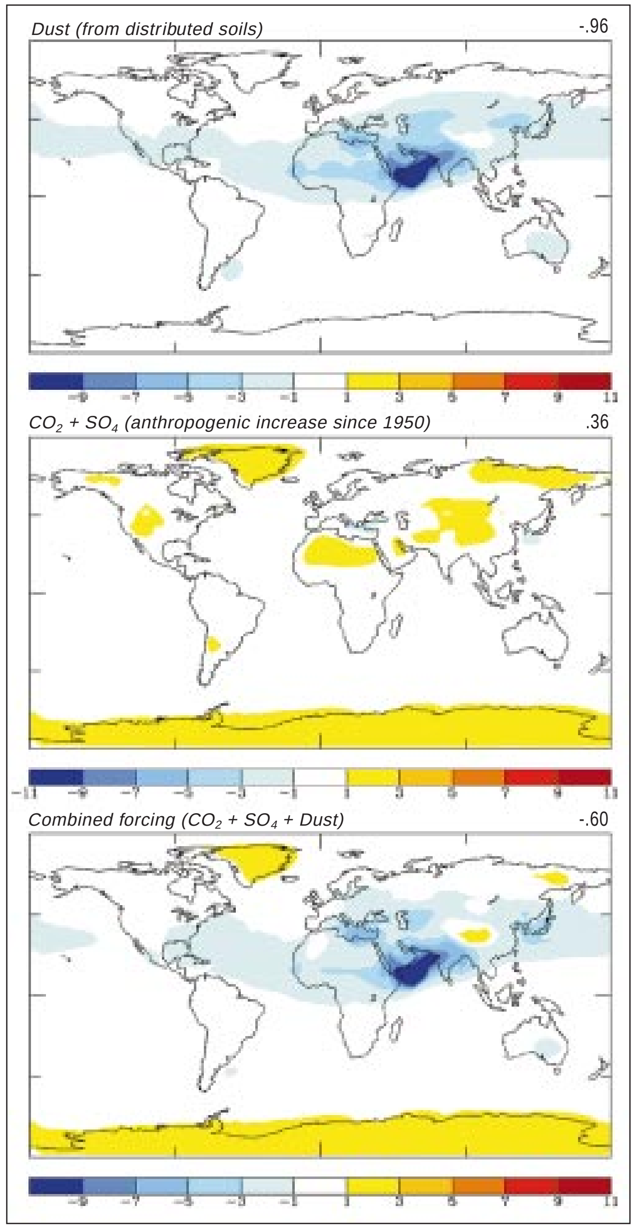
Stratospheric volcanic aerosols have had a well-documented effect of inducing climate cooling. The "year without a summer" (1816) is clearly associated with the eruption of Tambora in Indonesia in April 1815. The recent Mt. Pinatubo eruption (1991) is associated with Northern Hemisphere surface cooling of as much as 0.5˚C.

Sulfur dioxide (SO_2) from volcanic emissions is recognized as the major contributor to stratospheric aerosols. In the atmosphere it converts to sulfuric acid (H_2SO_4) via the OH radical. The amount of stratospheric aerosols and their effects on climate depend on the ability of the eruption to inject material into the stratosphere and on the sulfur content of the emissions. However, microphysical properties of the aerosol particles must be taken into account in reckoning whether their infrared absorptivity, which acts to warm the Earth, or their albedo effect, which acts to cool the Earth, will be dominant.

The presence of volcanic aerosols in the stratosphere has recently been tied to depletion of stratospheric ozone in temperate latitudes. The concept is that sulfate aerosols serve as sites for heterogeneous chemical reactions which have the effect of destroying ozone.

Tropospheric aerosols affect the radiative forcing of climate through three primary mechanisms: 1) Direct forcing in which radiation is scattered or absorbed by the aerosol particles; 2) indirect forcing in which enhanced concentrations of aerosol particles result in enhanced concentrations of cloud drops; and 3) the indirect effects of

Surface forcing caused by dust from disturbed soils is currently on the order of -1 Wm^{-2}, which is comparable in magnitude to the current effect of CO_2 and sulfate aerosols *(Tegen et al., 1996).*



aerosols on heterogeneous atmospheric chemistry (not discussed further in this chapter).

The direct radiative effects on climate of tropospheric aerosols are hard to assess because of the wide range of chemical compositions, time and spatial distributions, range of particle sizes and shapes, interactions with water vapor and clouds, and overall global variability that is dependent on both natural sources and human activities. Assessments of the indirect effects of tropospheric aerosols are even more difficult to make, yet they may be as significant as the direct effects.

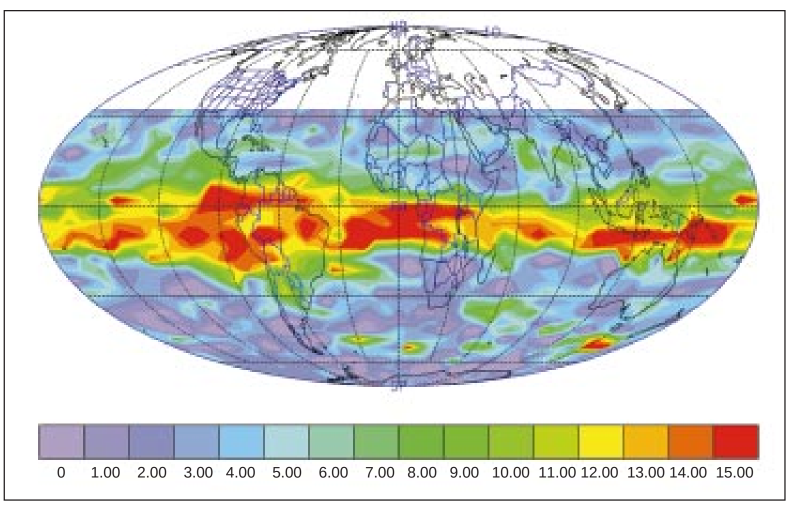
Volcanoes pose significant hazards for people and property on the ground, and the major challenge to satellite-based observations of volcanic hazards is the development of techniques that can be used in a predictive manner to detect an evolving volcanic crisis and to provide timely information to the relevant authorities on the ground. Thermal and deformation monitoring of numerous volcanoes that show signs of activity will be undertaken during the EOS era. The hazards associated with eruptions are diverse and numerous, and include the health hazards associated with low-altitude volcanic gases, and loss of life and property by inundation by lava flows, pyroclastic flows, and mud flows. There is also an increasingly frequent potential for unexpected aircraft encounters with volcanic plumes or clouds, with the potential catastrophic loss of life due to a major air crash.

Required Measurements and Data Sets

Measurements are required to assess the climate roles of stratospheric aerosols, tropospheric aerosols, and volcanic aerosol precursor gases, and to assess volcanic hazards.

For climate monitoring and prediction purposes, the stratospheric aerosol loading between 40 km and the tropopause should be measured. Column optical depth should be measured with a horizontal spatial resolution of 400 km and accuracy of 0.001. The vertical resolution should be 1 km. For tropospheric aerosols, the optical depth accuracy should be 0.01, and there should be measurements of particle size and vertical distribution. The primary volcanic gas associated with aerosol formation, sulfur dioxide, should be measured with 5-10% accuracy. For detection and avoidance of volcanic hazards, there should be measurements of plume altitude, dispersal rate, water vs. ash content, and plume temperature. For volcanic hazards on the ground, ground deformation at the cm-scale should be measured, along with thermal flux from active lava flows, lava lakes, and fumarole fields to an accuracy of ~10^4 Wm^{-2}. Surface topography should be measured at a spatial

Map of the Mt. Pinatubo SO_2 cloud from MLS *(Read et al., 1993).*



scale of ~25 m/pixel and vertical accuracy of ~5 m in order to aid in the numerical modeling of surface flows, i.e., lava, pyroclastic, or mud flows, and in the analysis of slope stability.

EOS Contribution: Expected Improvement in Knowledge and National Benefit

EOS will make considerable contributions to our knowledge of volcanic eruptions and their consequences for climate change. MODIS, MISR, ASTER, and ETM+ will be used to characterize the number, location, style, and duration of both lava-producing and explosive eruptions. Plume-top altitudes and topography provided by MODIS, ASTER, HIRDLS, and MISR will allow testing of physical models of plume rise and dispersal. Volcano topography will be derived from ASTER, VCL (Vegetation Canopy Lidar) and foreign-partner radars. Measurements of different aspects of sulfur dioxide abundance will be made by TOMS, OMI, TES, MLS, and ASTER. Several EOS instruments, SAGE III, EOSP, MISR, OMI, GLAS, and HIRDLS, will monitor stratospheric and tropospheric aerosols. Continuous measurements made by MODIS, CERES, and SAGE III will provide an important record of the effects of volcanic aerosols on the Earth's radiation budget and on global vertical profiles of atmospheric temperature and composition. GLAS on the EOS ICESat spacecraft and VCL will provide valuable information on the vertical and spatial extent of significant stratospheric and tropospheric aerosol layers.

Overall, the contribution of EOS will be to provide the global data necessary to allow understanding and prediction of aerosol changes as an essential aspect of assessing the causes of climate variability and climate change. EOS measurements will also enable the first truly global inventory of volcanic eruptions, as well as the high-temporal-resolution study of surface flows and eruption plumes in the stratosphere. Through a combination of multiple EOS instrument measurements, volcano hazard mitigation will also be improved because of the dramatic increase in the quantitative measurement of lava temperatures, gas emissions, surface topography, eruption plume tracking, and ground deformation.

Some EOS stratospheric aerosol products

Parameter Name	Units	Accuracy Abs::Rel	Temporal Resolution	Horizontal Resol:: Cover	Vertical Resol::Cover	Comments
SAGE-III Aerosol Extinction Profiles (7 wavelengths)	1/km	5% :: 5%	1 profile/ (2 min), 30/day	<2 × <1 deg :: Global	1 km :: 0-40 km	
HIRDLS Aerosol Extinction Coefficient	1/km	5-10% :: 1-10%	2 global maps /day [d, n]	400 × 400 km :: Global	1 km :: 5-60 km (given accuracies for 7-30 km)	

Acronyms

2D Two Dimensional

3D Three Dimensional

4DDA 4-Dimensional Data Assimilation

A

A/SA arid/semi-arid

AABW Antarctic Bottom Water

AASE II Airborne Arctic Stratospheric Expedition II

AATSR Advanced Along Track Scanning Radiometer

ACRIM I Active Cavity Radiometer Irradiance Monitor I

ACSYS Arctic Climate System Study

ADEOS Advanced Earth Observing System

AEAP Atmospheric Effects of Aviation Program

AERONET Aerosol Robotic Network

AESOPS Antarctic Environment Southern Ocean Process Study

AGCM atmospheric general circulation models

AHM (model)

AIRS Atmospheric Infrared Sounder

AIRSAR Airborne Synthetic Aperture Radar

ALOS Advanced Land Observation Satellite

ALT Altimeter

AMI Active Microwave Instrument

AMIP Atmospheric Model Intercomparison Project

AMLS Array MLS

AMSR Advanced Microwave Scanning Radiometer

AMSR-E Advanced Microwave Scanning Radiometer (EOS Version)

AMSU Advanced Microwave Sounding Unit

APAR Absorbed Photosynthetically-Active Radiation

ARM Atmospheric Radiation Measurement

ASAR Advanced Synthetic Aperture Radar

ASF Alaska SAR Facility

ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer

ATBD Algorithm Theoretical Basis Document

ATLAS Atmospheric Laboratory for Applications and Science

ATMOS Atmospheric Trace Molecule Spectroscopy

ATSR Along Track Scanning Radiometer

AVHRR Advanced Very High-Resolution Radiometer

AVIRIS Airborne Visible-Infrared Imaging Spectrometer

AWS Automatic Weather Stations

B

BAHC Biospheric Aspects of the Hydrological Cycle

BATS Biosphere-Atmosphere Transfer Model

BIOME Biogeochemical Information Ordering Management Environment

BOREAS Boreal Ecosystems Atmosphere Study

BRDF bidirectional reflectance distribution function

BSRN Baseline Surface Radiation Network

BUV Backscatter Ultraviolet

C

CALM Circumpolar Active Layer Monitoring

CART Cloud and Radiation Testbed

CASES Cooperative Atmosphere-Surface Exchange Study

CCD Charge-Coupled Device

CCN Cloud Condensation Nuclei

CDIAC Carbon Dioxide Information and Analysis Center

CDOM Colored Dissolved Organic Matter

CEM cumulus ensemble model

CERES Clouds and the Earth's Radiant Energy System

CESBIO Centre d'Études Spatiales de la Biosphère

CFC Chlorofluorcarbon

CH_2Cl_2 Dichloromethane

CH_3Cl Methyl chloride

$CHCl_3$ Chloroform

CHEM-1 Chemistry Mission-1

CLAES Cryogenic Limb Array Etalon

CLASS Canadian Land Surface Scheme

CLIVAR CLImate VARiability and prediction

ClO_x oxides of chlorine family

CMDL Climate Monitoring and Diagnostics Laboratory

COARE	Coupled Ocean-Atmosphere Response
COS	Carbonyl Sulfide
COSEPUP	Committee on Science, Engineering, and Public Policy
COV	Coefficient of Variation
CPR	Cloud Profiling Radar
CR	Correlation Radiometry
CRYSYS	Use of the Cryospheric System to Monitor Global Change in Canada (EOS IDS)
CTM	Chemistry and Transport Model
CZCS	Coastal Zone Color Scanner

D

DAAC	Distributed Active Archive Center
DAO	Data Assimilation Office
DAS	Data Assimilation System
DDL	Direct Downlink
DECAFE	Dynamique et Chimie de l'Atmosphere en Foret Equatoriale
DEM	Digital Elevation Model
DFA	Dual-Frequency radar Altimeter
DIC	Dissolved Inorganic Carbon
DMS	Dimethyl Sulfide
DMSP	Defense Meteorological Satellite Program
DOC	Dissolved Organic Carbon
DoD	Department of Defense
DoE	Department of Energy
DOM	Dissolved Organic Matter
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DT	Delta T (Temperature)
DU	Dobson Unit

E

ECHIVAL	European International Project on Climate and Hydrological Interactions between Vegetation, Atmosphere, and Land Surfaces
ECLIPS	Experimental Cloud Lidar Pilot Study
ECMWF	European Centre for Medium-Range Weather Forecasts
EDC	EROS Data Center
EFEDA	ECHIVAL Field Experiment in Desertification-Threatened Areas
EGIG	Expédition Glaciologique Internationale au Groenland
ENSO	El Niño-Southern Oscillation
ENVISAT	Environmental Satellite, ESA
EOS	Earth Observing System
EOS PM	EOS afternoon-crossing satellite
EOSDIS	EOS Data and Information System
EOSP	Earth Observing Scanning Polarimeter
EP	Earth Probe
ER-2	NASA Research Aircraft
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite
EROS	Earth Resources Observation System
ERS	European Remote-Sensing Satellite
ERS-1	European Remote-Sensing Satellite-1
ESA	European Space Agency
ESCC	Electrically Self-Calibrating Cavity
ESMR	Electronically Scanning Microwave Radiometer
ESSC	Earth System Sciences Committee
ET	Evapotranspiration
ETM	Enhanced Thematic Mapper
ETM+	Enhanced Thematic Mapper Plus
EURECA	European Retrievable Carrier

F

FAA	Federal Aviation Administration
FAO	Food and Agriculture Organization
FAPAR	Fraction Absorbed Photosynthetically Active Radiation
FIFE	First ISLSCP Field Experiment
FIRE	First ISCCP Regional Experiment
FLUXNET	Flux Network
FPAR	Fraction of Photosynthetically-Active Radiation
FSSP	Forward Scattering Spectrometer Probe
FTS	Fourier Transform Spectrometer

G

GAIM	Global Analysis, Interpretation, and Modeling
GAP	Gap Analysis Project
GCIP	GEWEX Continental-Scale International Project

GCM	General Circulation Model (also Global Climate Model)
GCOS	Global Climate Observing System
GCTE	Global Change in Terrestrial Ecosystems
GEBA	Global Energy Balance Archive
GENESIS	Global Environmental and Ecological Simulation of Interactive Systems
GEOS	Goddard Earth Observing System
GERB	Geostationary Earth Radiation Budget
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GFO	Geosat Follow-On
GGD	Global Geocryology Database
GHCN	Global Historical Climatology Network
GIS	Geographic Information System
GISP	Greenland Ice Sheet Program
GISS	Goddard Institute for Space Studies
GLAS	Geoscience Laser Altimeter System
GLCTS	Global Landcover Test Site Initiative
GLI	Global Imager
GLIMS	Global Land Ice Monitoring from Space
GLOBE	Global Learning and Observations to Benefit the Earth
GLOBEC	Global Ocean Ecosystem Dynamics
GMS	Geostationary Meteorological Satellite
GNP	Gross National Product
GOALS	Global Ocean-Atmosphere-Land System
GOES	Geostationary Operational Environmental Satellite
GOMOS	Global Ozone Monitoring By Occultation of Stars
GPCP	Global Precipitation Climatology Project
GPP	Gross Primary Productivity
GPS	Global Positioning System
GRDC	Global Runoff Data Center
GSFC	Goddard Space Flight Center
Gt	Gigaton
GTOS	Global Terrestrial Observing System
GVaP	GEWEX Water Vapor Project

H

HALOE	Halogen Occultation Experiment
HAPEX	Hydrological-Atmospheric Pilot Experiment
HCFC	Hydrochlorofluorocarbon
HH	Horizontal, Horizontal Polarization
HIRDLS	High-Resolution Dynamics Limb Sounder
HIRS	High-Resolution Infrared Radiation Sounder
HNLC	High Nutrient, Low Chlorophyll
HO_X	odd hydrogen family
HRDI	High-Resolution Doppler Imager
HSB	Humidity Sounder, Brazil
HSCT	High-Speed Civil Transport

I

IABP	International Arctic Buoy Program
ICESat	Ice, Clouds, and Land Elevation Satellite
ICRCCM	Intercomparison of Radiative Codes for Climate Models
ICSU	International Council of Scientific Unions
IDS	Interdisciplinary Science Investigation (EOS)
IFC	Intensive Field Campaign
IFO	intensive field observation
IFOV	Instantaneous Field of View
IGAC	International Global Atmospheric Chemistry
IGBP	International Geosphere-Biosphere Programme
IGPPDI	Global Primary Production Data Initiative
IHP	International Hydrological Program
ILAS	Improved Limb Atmospheric Spectrometer
IMAS	Integrated Multispectral Atmospheric Sounder
IOC	Intergovernmental Oceanographic Commission
IOP	Intensive Observing Period
IPCC	Intergovernmental Panel on Climate Change
IR	infrared
ISAMS	Improved Stratospheric and Mesospheric Sounder
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project
IT	Instrument Team
ITCZ	Inter-Tropical Convergence Zone
IWP	ice water path

J

JERS	Japanese Earth Remote-Sensing Satellite
JERS-OPS	Japanese Earth Remote-sensing Satellite-OPS
JGOFS	Joint Global Ocean Flux Study

JPLAIRSAR	JPL Airborne Synthetic Aperture Radar
JPO	Joint Planning Office

K

KINEROS	Kinematic wave overland flow, channel routing and Erosion model

L

LAI	Leaf-Area Index
Landsat	Land Remote-Sensing Satellite
LBA	Large Scale Biosphere-Atmosphere Experiment in Amazonia
LERTS	Laboratoire d'Etudes et de Recherches en Teledetection Spatiale
LHH	L-band HH
LIS	Lightning Imaging Sensor
LITE	Lidar In-space Technology Experiment
LOICZ	Land Ocean Interactions in the Coastal Zone
LS	Lower Stratosphere
LSM	Land-Surface Model
LSP	Land-Surface Parameterizations
LTER	Long-Term Ecological Research
LW	longwave
LWP	liquid water path

M

MAAT	Mean Annual Air Temperatures
MAPS	Measurement of Air Pollution from Satellites
MCS	mesoscale convective systems
MERIS	Medium-Resolution Imaging Spectrometer
METEOR-3	Russian Operational Weather Satellite
METOP	Meteorological Operational Satellite
MHS	Microwave Humidity Sounder
MIMR	Multifrequency Imaging Microwave Radiometer
MISR	Multi-angle Imaging Spectroradiometer
MIT	Massachusetts Institute of Technology
MLS	Microwave Limb Sounder
MM	mesoscale model
MMIC	Microwave Monolithic Integrated Circuit
MMS	Modular Modeling System
MODIS	Moderate-Resolution Imaging Spectroradiometer
MODLAND	MODLIS Land
MOPITT	Measurements of Pollution in the Troposphere
MOU	Memorandum of Understanding
MSG	Meteosat Second Generation
MSU	Microwave Sounding Unit
MT	Megaton
MVI	MODIS Vegetation Index

N

NAD	Nitric Acid Dihydrate
NADW	North Atlantic Deep Water
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency
NAT	Nitric Acid Trihydrate
NBIOME	Northern Biosphere Observation and Modeling Experiment
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NESDIS	National Environmental Satellite, Data, and Information Service
NEXRAD	Next Generation Weather Radar
NH	Northern Hemisphere
NIR	Near Infrared
NMC	National Meteorological Center
NMHC	Non-Methane Hydrocarbons
NOAA	National Oceanic and Atmospheric Administration
NOPEX	Northern Hemisphere Climate-Processes Land-Surface Experiment
NO_X	odd nitrogen family
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	Net Primary Production
NRC	National Research Council
NSCAT	NASA Scatterometer
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
NWP	Numerical Weather Prediction

O

OCS	Carbonyl Sulfide
OCTS	Ocean Color and Temperature Scanner
OH	Hydroxyl
OLR	Outgoing Longwave Radiation
OMI	Ozone Measuring Instrument
ONR	Office of Naval Research
ORNL	Oak Ridge National Laboratory
OSU	Oregon State University
OTTER	Oregon Transect Terrestrial Ecosystem Research

P

PAR	Photosynthetically-Active Radiation
PARCA	Program for Arctic Regional Climate Assessment
PEM	Production Efficiency Model
PI	Principal Investigator
PIK	Potsdam Institute for Climate Impact Research
PILPS	Project for Intercomparison of Land-Surface Parameterization (LSP) Schemes
PNZ	Phytoplankton-nutrient-zooplankton
POLDER	Polarization and Directionality of the Earth's Reflectance
POLES	Polar Exchange at the Sea Surface (IDS)
ppm	parts per million
PR	Precipitation Radar
PSC	Polar Stratospheric Cloud
PSU	Pennsylvania State University
PW	precipitable water

Q

QBO	Quasi-Biennial Oscillation

R

Radarsat	Radar Satellite, Canada
RAMS	Regional Atmospheric Modeling System
RC	radiative-convective
REP	Relativistic Electron Precipitation
RGPS	Radarsat Geophysical Processor System

S

S.D.	Standard Deviation
SAFARI	South African Fire—Atmospheric Research Initiative
SAGE	Stratospheric Aerosol and Gas Experiment
SALSA	Semi-Arid Land-Surface-Atmosphere
SAM	Stratospheric Aerosol Measurement
SAR	Synthetic Aperture Radar
SAVI	Soil-Adjusted Vegetation Index
SBUV	Solar Backscatter Ultraviolet
SCA	Snow-Covered Area
SCANSAR	Scanning Synthetic Aperture Radar
SCAR-B	Smoke Cloud and Radiation-Brazil
SCARAB	Scanner for Radiation Budget
SCF	Science Computing Facility
SCICEX	Submarine Arctic Science Cruise (Program)
SCOPE	Scientific Committee on Problems of the Environment
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEB	Surface Energy Balance
SEDAC	Socioeconomic Data and Applications Center
SGP	Southern Great Plains
SHEBA	Surface Heat Budget of the Arctic Ocean
SiB	Simple Biosphere Model
SIMIP	Sea Ice Model Intercomparison Project
SIR-C	Shuttle Imaging Radar-C
SLR	Satellite Laser Ranging
SMM	Solar Maximum Mission
SMM/I	Special Sensor Microwave/Imager
SMMR	Scanning Multispectral Microwave Radiometer
SOHO	Solar Heliospheric Observatory
SOLAS	Surface Ocean Lower Atmosphere Study
SOLSTICE	Solar Stellar Irradiance Comparison Experiment
SPCZ	South Pacific Convergence Zone
SPE	Solar Particle Event
SPOT	Systeme pour l'Observation de la Terre
SRB	Surface Radiation Budget
SRBEX	Susquehanna River Basin Experiment
SSALT	Solid State radar Altimeter
SSM/I	Special Sensor Microwave/Imager
SST	Sea-Surface Temperature
SSU	Stratospheric Sounding Unit
STP	Standard Temperature and Pressure
STS	Space Transport System

SVAT	Soil-Vegetation-Atmosphere Transfer Model
SVI	Spectral Vegetation Indices
SW	shortwave
SWE	Snow Water Equivalent
SWIR	Shortwave Infrared

T

T-S	temperature-salinity
TARFOX	Tropospheric Aerosol Radiative Forcing Observational Experiment
TEM	Terrestrial Ecosystem Model
TES	Tropospheric Emission Spectrometer
THM	Terrestrial Hydrology Model
TIR	Thermal Infrared
TM	Thematic Mapper
TMI	TRMM Microwave Imager
TMR	TOPEX Microwave Radiometer
TOA	top of the atmosphere
TOGA	Tropical Ocean Global Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOP	Terrestrial Observation Panel
TOPEX/ Poseidon	Ocean Topography Experiment
TOPORAD	(model)
TOPSAR	Topographic Synthetic Aperture Radar
TOVS	TIROS Operational Vertical Sounder
TRACE-A	Transport and Chemistry near the Equator over the Atlantic
TRAGNET	United States Trace Gas Network
TRMM	Tropical Rainfall Measuring Mission
TSI	total solar irradiance

U

UARS	Upper Atmosphere Research Satellite
UKMO	United Kingdom Meteorological Office
UMCP	University of Maryland, College Park
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USAF	United States Air Force
USDA	United States Department of Agriculture
USGCRP	U.S. Global Change Research Program
USGS	United States Geological Survey
UT	Upper Troposphere
UV	Ultraviolet
UV-B	Ultraviolet-B

V

VEMAP	Vegetation/Ecosystem Modeling and Analysis Project
VHRR	Very High Resolution Radiometer
VI	Vegetation Index
VIC	Variable Infiltration Capacity
VIRGO	Variability of solar Irradiance and Gravity Oscillations
VIRS	Visible Infrared Scanner
VIS	Visible
VNIR	Visible and Near Infrared
VOC	Volatile Organic Carbon

W

WCRP	World Climate Research Program
WDC-A	World Data Center-A
WFPS	Water-Filled Pore Space
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WSR	Weather Survelliance Radar

X

X-SAR	X-Band Synthetic Aperture Radar

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National Aeronautics and
Space Administration

January 1999

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