Chapter 1

Overview

Lead Author E. J. Barron

Contributing Authors D. L. Hartmann
M. D. King
D. S. Schimel
M. R. Schoeberl

Chapter 1 Contents

1.1 Introduction

NASA's Earth Observing System (EOS) was designed to initiate a new era of integrated global observations intended to advance our understanding of the entire Earth system on a global scale through developing a deeper understanding of the components of that system, their interactions, and how the Earth is changing. EOS plays a critical role in addressing a 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.

The EOS program was founded in response to a compelling scientific vision driven by recognition of the societal importance of the natural variability on our planet and realization that humans are no longer passive participants in the evolution of the Earth system. In 1979, the World Climate Research Program (WCRP) initiated an international effort to understand the physical basis of climate in response to droughts and floods that revealed societal vulnerability to climate variability. In 1982, a NASA workshop led by Richard Goody described the need for a scientific program designed to "ensure continuing habitability" of our planet in the face of the expansion of the human population and its activities. Then in 1986, the International Geosphere-Biosphere Program (IGBP) was initiated with the objective "to describe and understand the interactive physical, chemical, and biological processes that regulate the Earth's unique environment for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions."

A new view, based on an integrated programmatic framework, emerged as the central paradigm of both national and international programs. The foundation for this paradigm was a recognition that: 1) the Earth can be understood only as an integrated system; 2) each decade will likely bring a new specific environmental crisis for which the solutions must draw on years of accumulated understanding; and 3) science is a partner in decision-making, guided by the potential to benefit society and to enhance our economic security.

There is little doubt that an integrated Earth systems view would have eventually emerged as a product of the maturity of the Earth science disciplines and the powerful global and synoptic tools of study that have been developed over the last decades. However, a sense of urgency developed in direct response to the observations of ozone depletion over Antarctica, evidence of widespread tropical deforestation, and the record of increasing concentrations of carbon dioxide measured at Mauna Loa observatory and the related climate model predictions of global warming.

The Earth System Sciences Committee commissioned by NASA (ESSC 1988) provided the intellectual framework for an integrated research approach designed to address these critical issues. The report called for sustained long-term measurements of global variables to record the vital signs of the Earth system and the observations required to provide a fundamental description of the Earth and its component parts. The report urged that, as part of an integrated research approach, these observations must be intimately coupled to focused process studies, the development of Earth system models, and an information system that ensures open access to consistent, long-term observations of the Earth system.

A consistent view is obtained from the broad suite of National Research Council (NRC) (1985; 1986; 1988; 1990; 1992) reports that also call for an observing strategy that strengthens the base of knowledge in all the sciences that deal with the Earth, quantifies the magnitude of the driving forces for global change, and monitors the state of the Earth system and its "vital" signs. These reports call for an observing strategy that focuses on the highest priority measurements needed for each of the major disciplines of the Earth sciences and on the importance of simultaneity, calibration, and continuity of measurements to establish how the Earth is changing, and to develop and validate global predictive models.

The role of satellite systems in developing this research strategy is unique because of the capability to provide a long-term, consistent, calibrated, global set of observations. NASA's EOS was designed specifically in response to the recommendations of the ESSC and the NRC, and was instituted as an integral element of the U.S. Global Change Research Program (USGCRP).

The U.S. Global Change Research Program outlined an accelerated, focused research strategy designed to reduce key scientific uncertainties and to develop more-reliable predictions. The research priorities of the USGCRP are based on a series of policy-relevant questions that reflect areas of substantial uncertainty (Table 1.1). The evolution of the USGCRP has continued to sharpen the set of questions as a result of discovery and debate. EOS objectives, and associated critical measurements, encompass many of the priorities outlined by the USGCRP and include contributions in seven disciplinary areas, each of which is the subject of a chapter in this 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

The scientific challenges within each of these major research areas define an observation strategy in which simultaneity, calibration, and continuity are critical ingredients.

The evolution of the USGCRP has also resulted in a clearer call to address the implications of global change through assessments of impacts, and a greater focus on the most policy-relevant themes. 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 dimensions”) 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.

1.2 EOS science contributions

The EOS science contributions begin with a commitment to measuring 24 critical variables (Table 1.2). These 24 measurements are a foundation for a coordinated research program addressing the highest priority elements of the USGCRP.

1.2.1 Radiation, clouds, water vapor, precipitation, and atmospheric circulation

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 re-radiated to space from the Earth. The rate of re-radiation is controlled by both the amount and the vertical distribution of not only the clouds and aerosol particles but also the atmospheric 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 and also interacts strongly with the thermal structure of the atmosphere.

Understanding the interactions among the various elements mentioned 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.

1.2.1.1 Total Solar Irradiance (TSI)

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, 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.

Table 1.1

What is the role of clouds in the Earth's radiation and heat budgets?
How do the oceans interact with the atmosphere in the storage, transport, and uptake of heat?
How will changes in climate affect temperature, precipitation, and soil moisture patterns, and the general distribution of water and ice on the land surface?
How can the reliability of global- and regional-scale climate predictions be improved?
What is the relative importance of the oceans and terrestrial biosphere as sinks for fossil fuel carbon dioxide, and how do they change with time?
What are the major sources responsible for the current increases in atmospheric nitrous oxide and methane?
What are the implications for stratospheric ozone, globally and in polar regions, of increased concentrations of chlorine and bromine?
What ecological systems are most sensitive to global change, and how can natural change in ecological systems be distinguished from change caused by other factors?
What are the likely rates of change in ecological systems due to global change, and will natural and managed systems be able to adapt?
How do ecological systems themselves contribute to processes of global change?
What are the natural ranges and rates of change in the climate and environmental systems?
How rapidly have ecosystems adapted to past abrupt transitions in climate?
Do past warm intervals in Earth history provide appropriate scenarios to test model predictions of future global warming?
What kinds of empirical data are needed to measure and understand human interactions in global change?
How and why do human beings and human systems influence physical and biological systems?
How do different coastal regions respond geologically and ecologically to higher sea level, and how can the contributions from changes in climate (e.g., glacier melting and ocean warming) be differentiated from those due to tectonic processes?
What are the magnitude, geographic location, and frequency of volcanic eruptions and their effect on climate?
How do permafrost regions of the Northern Hemisphere respond to climate warming?
What aspects of solar variability are influencing the stratospheric ozone layer?
What impacts do other inputs, e.g., particles, have on the upper atmosphere and how are they coupled to other atmospheric regions?
How does the sun's output vary and what is the impact on terrestrial climate?

Policy-relevant questions addressed by the USGCRP, including EOS.

Table 1.2

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+***

Key physical variables needed to advance understanding of the entire Earth system and the interactions among the components. The EOS instruments listed in bold font are primary sensors, bold italics represent secondary instruments, and roman fonts are contributing instruments for critical measurements.

NASA's EOS directly addresses this critical issue:

- EOS has the potential to determine TSI with 0.001% relative precision by using overlapping flights of the ACRIM instrument with 0.1% absolute accuracy. This precision is sufficient to detect climatically-significant changes.

1.2.1.2 The role of radiation fluxes in the climate system

The climate system is a heat engine that is driven by the spatial and temporal distribution of the entry and exit of broadband radiant energy. Radiation is the primary forcing element in climate change. Modern climate models have consistently indicated that CO_2 and other anthropogenic trace gases will change the vertical distribution of radiative fluxes in the atmospheric column so as to warm the troposphere and cool the stratosphere.

Radiation is important for climate feedback. 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, posing the most formidable obstacle to climate prediction by general circulation models (GCMs). We cannot reliably predict the climate response to a given radiative forcing because of the uncertainty in the cloud/climate feedback to changes in radiation at the Top of the Atmosphere (TOA). 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. 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 0.2-2 Wm^{-2}. Although 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, our knowledge of the global distribution of aerosols is inadequate to assess their role in future climate.

The surface of the Earth absorbs about twice as much solar radiation as does the atmosphere. 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 Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget (SRB) Project has found that errors in both shortwave and longwave radiation measurements over snow and ice surfaces and for longwave radiation in persistently cloudy regions are larger than those in other regions. Surface albedos and radiative fluxes over snow-free land are also not known to sufficient accuracy. Until surface albedo of all land surfaces is known to greater accuracy, it will not be possible to quantify adequately the radiative forcing to climate that is associated with changes in land use. Despite their importance, TOA shortwave and longwave radiative flux measurements currently available 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. The surface energy budget also provides a key forcing to ocean circulation so that more-accurate information is needed in this aspect of radiation studies as well.

NASA's EOS directly addresses many of these critical issues:

- EOS will contribute to improved understanding of the effects of the atmospheric trace gases by producing more-accurate vertical profiles and time histories of water vapor and radiatively active gases and by validating the radiative transfer physics for both the natural and anthropogenic gases in the atmosphere.

- The EOS instrument Clouds and the Earth's Radiant Energy System (CERES), along with other EOS instruments such as the Multi-angle Imaging Spectroradiometer (MISR) and the Earth Observing Scanning Polarimeter (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-to-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.

- EOS instruments MISR and EOSP will significantly advance our understanding of the distribution and radiative character of atmospheric aerosols.

- EOS will determine the surface albedo of all land surfaces to a greater accuracy, providing the possibility to better quantify the radiative forcing due to land use and land-cover changes.

- The retrieval of longwave radiation measurements will be improved by combining satellite measurements with data from ocean-based monitoring stations that would provide both SRB and cloud-base heights.

1.2.1.3 The role of convection and clouds in climate

Clouds not only affect the radiative energy fluxes in the atmosphere through scattering, absorption, and re-radiation, but vertical motions associated with them produce important convective transports of energy and moisture. Clouds produce 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 TOA. Convection associated with clouds also affects the exchange of heat between the surface and the atmosphere. The cloud type that appears to exert the greatest effect on climate sensitivity in state-of-the-art global GCMs is the tropical mesoscale anvil cloud that accompanies cumulus convection. The central question is how to represent such features as the detrainment of ice from cumulus updrafts into anvil clouds.

Scale is also a critical issue in understanding and predicting atmospheric circulation systems. 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. Development and validation of these models and their parameterizations are important objectives in atmospheric sciences.

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 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.

NASA's EOS directly addresses many of these critical issues:

- EOS observations will provide data for validation on three scales (global, regional, and cloud-resolving), and EOS interdisciplinary modeling investigations focus on a range of efforts that range from 100-year integrations (global), to 10-day integrations (regional), to 1-day (cloud resolving).

- The Lightning Imaging Sensor (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, will address key questions regarding cloud characteristics that are faced by climate modelers.

- 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.

- TOA radiative flux measurements from space will enter their fourth generation with the CERES instruments on the Tropical Rainfall Measuring Mission (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-to-4 lower than the ERBE errors.

- In the EOS time frame, calculated shortwave surface flux accuracies should increase greatly as more-accurate cloud (Visible Infrared Scanner [VIRS], Moderate-Resolution Imaging Spectroradiometer [MODIS]), atmospheric (AIRS), and surface (MISR, MODIS) properties become available.

- In the EOS time frame, improved tropospheric water vapor determinations will help better determine downward longwave fluxes. The water vapor determinations will be available from the AIRS/Humidity Sounder from Brazil (HSB) instruments and, over land, from MODIS.

- Active systems such as the Geoscience Laser Altimeter System (GLAS) lidar from EOS and a proposed 94-GHz cloud radar may offer the best solution to the large uncertainty in the calculations of downward longwave flux at the surface due to uncertainties in cloud overlap.

- The EOS MODIS instrument has design capabilities specifically directed toward cloud-property determinations. Very-high-spatial-resolution measurements from the EOS Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), multi-angle EOS MISR data, polarization of cloud particles determinations 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 data from the passive sensors just cited with data from EOS GLAS (the active laser 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 improvements in the determinations of these cloud properties.

1.2.1.4 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. Climate feedbacks are sensitive to the vertical distribution of both water vapor and temperature. 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.

NASA's EOS directly addresses many of these critical issues:

- Data from EOS instruments will improve the quality of global measurements of the water vapor distribution. In particular, the EOS instruments, AIRS, Advanced Microwave Sounding Unit (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.

- EOS cloud and moisture measurements, when combined with wind estimates from data assimilation techniques 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.

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

- AIRS/AMSU/HSB, and the EOS instruments High-Resolution Dynamics Limb Sounder (HIRDLS) and Microwave Limb Sounder (MLS) will supply improved horizontal and vertical resolution temperature and moisture measurements. Also, the EOS Stratospheric Aerosol and Gas Experiment III (SAGE III) instrument will provide very accurate monitoring of water vapor trends in the stratosphere.

1.2.1.5 Precipitation

Rainfall plays a central role in governing the climate of the Earth. The latent heat release in convection is a major source of energy that drives the general circulation of the atmosphere. 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 jet streams, and altering rainfall patterns in midlatitudes. Precipitation is also of critical importance to human systems and the distribution and character of life.

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 shown 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, and they also underestimate the frequency of occurrence of the light-rain category. Satellite rainfall retrieval algorithms play a vital role in producing realistic global rainfall distributions because it is impossible to set up uniform networks of rain gauges over the entire globe.

NASA's Earth Science Enterprise directly addresses many of these critical issues:

- TRMM employs a suite of sensors including one microwave (TRMM Microwave Imager [TMI]), one visible (VIS)/infrared (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 and subtropics. Within the EOS measurement system, the key instruments for precipitation measurement are the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) and HSB on the EOS PM-1 platform.

1.2.1.6 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.

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.

NASA's EOS makes a number of important contributions in addition to those described above:

- The EOS QuikSCAT, followed by the SeaWinds instrument on the Japanese Advanced Earth Observing System II (ADEOS II) 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.

1.2.2 Ocean circulation, productivity, and exchange with the atmosphere

The oceans of the world play a key role in modulating climate. The ocean is a major agent in the equator-to-pole redistribution of heat. The positions of major current systems such as the Gulf Stream, the Kuroshio, and the Antarctic circumpolar current are major factors in governing temperature patterns and the transport of nutrients, chemicals, and biota. Models of ocean circulation are well-developed, although coupled models of ocean physics and biogeochemistry are in the initial stages of development.

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 (methyl bromide exchange is also of interest). Among questions that need to be resolved are: 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; and 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 oceans are a sink for carbon dioxide, and hence play a key role in moderating the effects of increased carbon dioxide on global warming.

The ability to forecast well in advance the timing and geographic extent of season-to-interannual climate anomalies is predicated on the thermal inertia of the climate system, which is based on the slow response to forcings of the oceans as compared to the more-rapid forcings of the atmosphere.

Air-sea momentum fluxes and near-surface winds modulate the coupling between the atmosphere and the ocean. Wind stress is the largest single source of momentum in the upper ocean, and air-sea momentum fluxes substantially influence large-scale upper-ocean circulation, smaller-scale mixing, and the detailed shape of the sea surface on all scales.

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. However, observations in the data-sparse areas of the southern and tropical oceans are insufficient to provide reliable estimates of the surface turbulent and radiative fluxes.

Freshwater forcing is an important aspect of the global water balance. Local freshwater at the ocean surface limits exchanges of heat and moisture with the atmosphere. In the atmosphere, fluxes of heat and moisture drive tropospheric 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.

Major climate-related factors that contribute to sea-level rise are thermal expansion in 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 recent changes in sea level as well as predicted future changes. Ocean tides cause a larger sea-level signal than temporal changes in ocean circulation and sea level so that an accurate tidal model is required to remove the tidal signal for studies of ocean circulation.

NASA's EOS directly addresses many of these critical issues:

- The EOS Jason-1 radar altimeter (Poseidon 2) will serve to determine multi-decadal global sea-level variations and their long-term trends; and the Advanced Microwave Scanning Radiometer-EOS Version (AMSR-E) and SeaWinds measurements will contribute wind-stress information as above.

- 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 kelvin. EOS AMSR-E will provide SST measurements with an accuracy of 1-to-1.5 K in all weather conditions, providing substantial additional information on the role of the oceans in the Earth's heat and hydrologic cycles.

- The EOS MODIS instrument will also be key for the measurement of ocean color. These data will be used to estimate phytoplankton abundance and productivity, as well as the amount of dissolved organic material and suspended particulate material. MODIS will also measure sun-stimulated fluorescence from chlorophyll, which will greatly improve estimates of upper ocean productivity.

- Several EOS interdisciplinary science investigations (IDS) focus on the interactions between the atmosphere and ocean across the sea surface. EOS worldwide observations of ocean surface wind stress by the SeaWinds scatterometer instruments, with accuracies of 10-to-12% in speed, will be critical to achieving these objectives. In addition, the EOS AMSR-E passive microwave instrument will provide complementary continual observations of wind speeds and stress magnitudes over the oceans.

- IDS studies of the ocean's biological system and its interplay with the ocean circulation and the global carbon cycle will be the focus of several EOS science teams. Long-term, well-calibrated measurements of ocean color from the EOS MODIS sensors and from the NASA Sea-viewing Wide Field-of-View Sensor (SeaWiFS) are essential for these studies. These data will be combined with physical measurements (such as scatterometer winds and radar altimetry) in numerical models to study both open ocean and coastal ocean processes.

1.2.3 Atmospheric chemistry and greenhouse gases

The interaction of biological, geochemical, and photochemical processes, the so-called biogeochemical processes, affect the global carbon dioxide, carbon monoxide, methane, nitrous oxide, and ozone budgets. Six major factors drive global change, and therefore, EOS research.

First, 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.

Second, 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.

Third, 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.

Fourth, 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.

Fifth, 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.

Sixth, 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.

NASA's EOS provides many key data products and analyses:

- EOS products will encompass many aspects of the carbon cycle, including provision of a global database of high-resolution analyses of land-cover change, estimates of the contribution of biomass burning to atmospheric CO_2, and trends in carbon fixation by terrestrial vegetation determined from observed changes in leaf-area index (LAI) and fraction of photosynthetically-active radiation.

- EOS will provide estimates of the extent and duration of inundation of wetlands and land cover, important elements in assessing methane production and oxidation.

- The EOS Tropospheric Emission Spectrometer (TES) will provide measurements related to nitrous and nitric oxide production and abundance.

- Ozone and related species will be monitored using EOS instruments, particularly those on the CHEM-1 mission. The Measurements of Pollution in the Troposphere (MOPITT) will make measurements of carbon monoxide and methane. MODIS observations of fire will lead to estimates of biomass burning contributions of hydrocarbons, methane, oxides of nitrogen, and nonmethane hydrocarbons to ozone production.

1.2.4 Land ecosystems and hydrology

Changes in land-surface processes and properties interact with, and cause changes in, both regional and global climate. The land-surface models that are utilized to assess these interactions generally contain formulations for surface radiation fluxes, turbulent and mass fluxes, liquid water fluxes, and control of water vapor and CO_2 fluxes by vegetation. However, these models still exhibit major differences in their predictions, and current models still do a poor 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. Land-surface properties such as type of cover, LAI, roughness length, and albedo are essential variables to address these limitations. Realistic representations of land-surface cover and moisture characteristics are likely to improve both climate and weather forecasting capabilities. There are also important questions regarding the interactions and feedbacks between the atmosphere and the surface in cases where the biosphere changes in response to elevated levels of atmospheric carbon dioxide.

Changing climate and land-surface characteristics may combine to change precipitation patterns, surface-water partitioning and storage, and river flows. Of further concern are the land processes that may alter water quality: erosion, sedimentation, and river biogeochemistry. One of the major objectives of research must be to improve hydrologic understanding at critical human scales. Thus key science issues for land-hydrology are to identify and quantify key hydrologic variables across a range of scales, and to develop or modify hydrologic process models to take advantage of operational and realistic data sources. The hydrologic variables that require more study include 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.

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.

NASA's EOS contributes substantially to addressing these issues:

- EOS vegetation measurements will range from 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 LAI, fraction of photosynthetically-active radiation that is absorbed, albedo, and vegetation indices are derived from direct measurements. A key derived product is net primary production (NPP), and the EOS 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.

- ASTER, operating in the visible, shortwave infrared, and thermal infrared, will provide surface reflectances and radiative (brightness) temperatures with 15-to-90-m resolution depending on wavelength. 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.

- The Enhanced Thematic Mapper+ (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 near-infrared channels, and 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, surface temperature and fire, plus biophysical variables such as LAI and fraction of photosynthetically-active radiation.

1.2.5 Cryospheric Systems

The cryosphere is an integral part of the global climate system, with important linkages and feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, and atmospheric and oceanic circulation. Because of the sensitivity of the cryosphere to temperature changes, accurate information on the rate and magnitude of changes in cryospheric elements (ice sheets, sea ice, snow cover, lake ice, permafrost) is essential. In particular, the potential for ice-sheet melting and associated sea-level rise under conditions of global warming is a central concern. High-latitude regions exhibit the greatest warming in response to higher levels of greenhouse gases in many GCM experiments. Unfortunately, climate models do not yet provide accurate meteorological simulations over the polar regions. Further, significant improvements in the representation of cryospheric processes and in understanding cryosphere-climate linkages and feedbacks are required to reduce uncertainties in the prediction of high-latitude climate change.

Realistic simulation of snow cover in climate models is essential for correct representation of the surface energy balance, as well as for understanding winter water storage and predicting year-round runoff. The lack of meteorological and snow-cover data to execute, calibrate, and validate snow-cover models is a major obstacle to improved simulations. Positive feedbacks involving sea ice and climate change have also been treated rather simply in global climate models although studies have shown that this important feedback is dependent on lead fraction, melt ponds, ice-thickness distribution, snow cover, and sea-ice extent. Glacier mass balance, and the potential for rapid ice-sheet thinning and sea-level rise, represents one of the most significant issues in assessing the impact of future climate change. Several issues limit our knowledge: large uncertainties in current ice-sheet mass balance estimates, questions of how climate change will be manifested and amplified in polar regions, the difficulty of predicting how atmospheric circulation and precipitation will change at high latitudes, uncertainties in the “fast physics” of ice flow, and questions concerning the characteristics of “triggers” for rapid change in ice flow (e.g., ice-shelf basal melting).

The major scientific challenges are: 1) to quantify the exchanges of freshwater between the hydrosphere and cryosphere, 2) to understand the role of such exchanges in climate variability and change, and 3) to improve the ability to simulate the important geophysical properties and processes controlling energy exchanges in the cryosphere. Long-term, consistent data sets are required to document changes in the cryosphere and to validate transient simulations using global climate models. Without a more thorough analysis of ice-sheet, snow-cover and sea-ice mass balance, it will be difficult to develop more-comprehensive models of the cryosphere.

NASA's EOS directly addresses many of these critical issues:

- MODIS will provide near-daily global coverage of snow-covered versus snow-free areas, and with MODIS' on-board visible/near-infrared calibrators, radiances of snow can be calculated. AMSR-E will provide a weekly snow extent product that will extend the long-term time series of passive microwave-derived snow extent started in 1978. The higher spatial resolution of AMSR-E compared to the Scanning Multispectral Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SSM/I) will improve the ability to map snow cover in forested regions. Combined, MODIS, AMSR-E, MISR, and ASTER will provide detailed, multi-sensor information on snow-cover extent, albedo, and surface temperature.

- EOS scientists are developing and validating algorithms that will use AMSR-E data to determine snow-water equivalent, an important parameter for weather forecasting and climate model validation.

- AMSR-E will provide data for deriving estimates of sea-ice concentration and sea-ice type, extending time series of ice extent in both polar regions and adding to the information on seasonal and interannual variability in the fraction of open water.

- ASTER and ETM+ provide the opportunity to monitor and detect changes in permafrost through measures of land cover, snow cover, snow depth, soil moisture, surface reflectance, surface temperature, and surface-displacement features.

- ASTER and ETM+ provide opportunities for increasing spatial and spectral resolution and repeat imaging capability of surface ice-sheet features.

- The Geoscience Laser Altimeter System (GLAS), by accurately measuring ice-sheet topography, will enable improved ice-flow models to be developed. With repeated measurements GLAS will reveal changes in surface elevation and hence mass balance of the ice sheets.

1.2.6 Ozone and Stratospheric Chemistry

Ozone influences climate. For instance, removal of ozone from the stratosphere causes cooling of the stratosphere and a small, but non-negligible, offset to the greenhouse forcing from CO_2, N_2O, CH_4, and CFCs. The size of the radiative forcing due to stratospheric ozone loss is very sensitive to the profile of the ozone loss. Seasonal changes are determined by the winter-summer changes in the stratospheric circulation. Interannual changes are linked to the eleven-year solar cycle in ultraviolet (UV) input from the sun and to the amount of volcanic aerosols in the stratosphere. Superimposed on these variations are anthropogenic changes related to the release into the atmosphere of human-made chemicals containing chlorine.

The most significant departures from normal have been changes in Antarctic polar ozone, leading to the phenomenon known as the ozone hole. Not until 1996 had changes in Arctic polar ozone been detected that are comparable to the changes in the Antarctic polar ozone. In recent decades it has become clear that there are also significant decreases in stratospheric ozone in midlatitudes as well.

The basic outline of the chemical processes that control stratospheric ozone appears to have been established, and changes in stratospheric ozone distribution have been accounted for in terms of chemical processes, transport, interactions with aerosols and polar stratospheric clouds, and interactions with solar ultraviolet radiation and energetic particles. However, a number of issues remain. 2D ozone models are not able to provide accurate representations of the ozone trends that were observed in middle and high latitudes over the 1980-to-1990 time period, while the 3D models suffer from unrealistic temperature fields which, in turn, alter the photochemistry. Variability in ultraviolet radiation reaching the Earth leads to changes in global total ozone. Energetic particle flux variations from the sun may also drive natural ozone variations. Both natural changes and human-made changes must be understood and separated if we are to have a firm understanding of how stratospheric chemistry will evolve.

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 polar stratospheric cloud information; and the need for solar-ultraviolet flux determinations. In addition there must be a concerted effort at validating the satellite measurements.

NASA's EOS provides many key contributions:

- EOS limb sounders (MLS and 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 OH measurements that were not previously available.

- The SAGE III instrument will provide many advances including the first satellite measurements of the size distribution of polar stratospheric clouds.

- Fully interactive chemical dynamical models are being developed especially for interpretation of EOS data.

- Wind fields provided by the NASA/Goddard Space Flight Center (GSFC) Data Assimilation Office (DAO) are of sufficient quality to remove the dynamical uncertainty from tracer observations.

1.2.7 Volcanoes and climate effects of aerosols

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 weather with a time scale of a few years. Sulfur dioxide released from the magma may be oxidized to sulfuric acid aerosols in the stratosphere, where they may reside for a year or more, generally producing cooling at the Earth's surface. 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.

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. 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.

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. 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 are 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. 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.

NASA's EOS directly addresses many of these critical issues:

- MODIS, MISR, ASTER, and ETM+ will be used to characterize the number, location, type, 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, Vegetation Canopy Lidar (VCL), and foreign-partner radars.

- Measurements of different aspects of sulfur dioxide abundance will be made by the Total Ozone Mapping Spectrometer (TOMS), the Ozone Monitoring Instrument (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-1 spacecraft and the Vegetation Canopy Lidar (VCL) will provide valuable information on the vertical and spatial extent of significant stratospheric and tropospheric aerosol layers.

- 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.

1.2.8 National and international contributions to major field campaigns

EOS observations and studies described above also support considerable surface observation efforts and major field campaigns. Examples of major programs include:

- FIRE (the First ISCCP Regional Experiment) is an ongoing multi-agency international program to support the development of improved cloud radiation parameterization schemes.

- GEWEX (Global Energy and Water Cycle Experiment) 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. GCIP (GEWEX Continental-Scale International Project) focuses on determination of the variability of the Earth's hydrological cycle and energy exchange budget over a continental scale.

- CLIVAR (for climate variability), a major project of the World Climate Research Program (WCRP), seeks to understand and predict climate variability on interannual-to-centennial time scales.

- GOALS (Global Ocean, Atmosphere, Land System), a major element of CLIVAR, directed to the study of seasonal-to-interannual variability.

- DEC-CEN (for decadal-to-century variability), a major element of CLIVAR, directed to the study of decadal-to-century time-scale natural variability and the role of human activities in modifying climate.

- JGOFS (Joint Global Ocean Flux Study), dedicated to satisfying critical elements of the IGBP, designed to study biogeochemical processes in the ocean and their role in climate change.

- GLOBEC (U.S. and International Global Ocean Ecosystem Dynamics program) with the goal of determining how marine animal populations respond to climate variability and long-term climate change.

- ARM (Atmospheric Radiation Measurement) Program, the largest contribution of the Department of Energy (DoE) to the 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, and to measure water vapor, temperature, and wind profiles throughout the lower atmosphere.

- BSRN (Baseline Surface Radiation Network), an international program of the WCRP designed to improve the accuracy and sampling rate of surface-measured shortwave and especially longwave radiative fluxes.

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

- ACSYS (Arctic Climate System Study), a WCRP project aimed at improved understanding of the role of the Arctic in the climate system, and studying global climate change and variability in the Arctic.

- SHEBA (Surface Heat Budget of the Arctic Ocean), a multi-national project whose goals are to develop and test models of Arctic ocean-atmosphere interactions and to improve the interpretation of satellite remote-sensing data in the Arctic.

- BOREAS (Boreal Ecosystems Atmosphere Study), a large-scale international field experiment, with the objective of improving our understanding of the exchanges of radiative energy, heat, water, carbon dioxide, and trace gases between the boreal forest and the lower atmosphere.

1.3 Measurement strategy

EOS and follow-on missions serve a unique and valuable role in meeting global change objectives, including: repetitive, synoptic coverage of the Earth-atmosphere-ocean system; observations in spectral bands from the ultraviolet to the microwave, depending on application; problem-appropriate spatial resolution; and absolute radiometric calibration. No other current or planned remote-sensing system matches this combination of capabilities. In order to accomplish the measurement objectives of EOS, together with an awareness of multi-agency and multi-national satellite observing systems, EOS has developed a measurement strategy that includes:

1) Simultaneous observations with a group of sensors on the same platform (satellite) that, taken together, improve either the accuracy or the scientific content of observations in comparison with measurements from a single instrument. This strategy depends on a close coordination in space and time, and is generally easier, if not absolutely required, on a single satellite.

2) An overlap strategy such that sensors can be intercompared and intercalibrated in order to construct long-term climate records. This strategy depends on using similar or identical sensors in orbit at the same time, but not necessarily in the same orbit or observing the same locations at the same time.

3) A diurnal sampling strategy for rapidly varying systems or ones with significant temporal variation (most notably clouds) in which more than one satellite is in orbit at the same time (preferably one sun-synchronous and one precessing).

4) A calibration strategy required to perform intra-system and intersystem data comparisons for global change research and monitoring.

5) A data continuity strategy that does not mandate the cloning of the existing satellite systems but retains the scientifically essential capabilities of the EOS systems.

1.3.1 Simultaneous observations

Specific examples where simultaneous observations are vitally important to meeting the measurement objectives, or are necessary to have sufficient accuracy to enable health and property impacts to be accurately assessed are:

1) Cloud properties (amount, optical properties, height) derived from MODIS (or comparable well-calibrated multi-spectral imager) must be coincident in space and time with radiative energy fluxes (top of atmosphere, surface) derived from CERES. Due to the high temporal variability of cloud systems and the spatial variability of clouds at spatial resolutions as small as several hundred kilometers, it is necessary for a broadband sensor (like CERES) to be on the same platform or have simultaneity between three and six minutes with a multi-spectral visible-infrared imager (like MODIS).

   If MODIS were to fail and CERES continue to operate, the radiation budget at the TOA (cloud radiative forcing) could still be derived, analogous to what was done with the Earth Radiation Budget Experiment (ERBE) between 1984 and 1989, but the cloud feedback could not. In this way, one could see what clouds en masse were doing to the Earth's atmosphere, but it would not be possible to determine whether the cloud forcing was due to changes in cloud type, vertical distribution, or amount.

   If CERES were to fail but MODIS continue to operate, the cloud radiative and micro-physical properties (cloud phase, particle size, vertical distribution, etc.) could be determined, but not their radiative effect on climate either at the TOA or at the Earth's surface. The strategy that EOS has adopted to date is to baseline CERES and MODIS on the same platform (AM-1 and PM-1) to enable the enhanced science of cloud forcing and cloud feedback (response) to be performed.

2) Atmospheric temperature and humidity determinations require, at present, a combination of sensors. The EOS PM-1 satellite will include an advanced sounder system (AIRS, AMSU, and HSB). The three instruments together are necessary to obtain both temperature and moisture profiles in the Earth's atmosphere using both infrared and microwave sensors. The current National Oceanic and Atmospheric Administration (NOAA) operational sounding system (TIROS Operational Vertical Sounder [TOVS]) also includes a suite of three sensors measuring both infrared (High-Resolution Infrared Radiation Sounder [HIRS]) and microwave (AMSU, MHS) radiation. NOAA depends on this full system for weather forecasting and currently launches a replacement satellite if one of these sensors fails.

This is therefore, as currently implemented, a simultaneity requirement involving three sensors.

3) Ocean surface topography, as demonstrated on the Ocean Topography Experiment (TOPEX)/Poseidon and later this century on the joint U.S.-France Jason-1 satellite, involves a dual frequency altimeter, ranging system, and microwave radiometer. Once again, this suite of sensor capabilities can be flown together on a single satellite (as TOPEX/Poseidon and Jason-1) but a combination of 3 sensors is required to achieve an accuracy requirement of 3 cm at the ocean surface. The microwave radiometer is used to make water vapor (pathlength) corrections to the radar altimeter measurements, thereby improving their accuracy.

Other examples where simultaneity is desirable, but not absolutely required, or where the accuracy would be severely degraded without simultaneity, include:

a) Tropospheric chemistry (precursors—the accuracy of methane (CH_4) and carbon monoxide (CO) measurements to be obtained from the Canadian-built MOPITT instrument, scheduled to be flown on EOS AM-1 in late 1998, is enormously enhanced by the ability to use MODIS to derive a cloud mask at a 1-km spatial resolution. Without the ability to have nearly simultaneous high-spatial-resolution measurements of cloud cover, the much coarser resolution MOPITT (22-km pixels) would have partially-filled fields of view that would contaminate the signal and degrade the accuracy of the CH_4 abundance and CO concentration determinations. It is not possible to quantitatively estimate the accuracy loss that would result without the presence of a high-resolution multispectral imager onboard the same spacecraft.

b) Measurements of fire occurrence and volcanic effects over the land are aided by having a global surveyor with moderate-to-high spatial resolution (e.g., MODIS) that can determine the presence and location of fires, molten lava from volcanic eruptions, and burning oil wells, and then be used to schedule the acquisition of high spatial resolution, limited coverage sensors such as Landsat-7/ETM+ or AM-1/ASTER, each of which is able to obtain only about 100 scenes globally per day. This telescoping ability to find a hot thermal anomaly and subsequently to acquire high resolution imagery of the affected area, is exceedingly valuable. On the other hand, there is no requirement whatsoever that these measurements be made simultaneously in space or time, only that both capabilities exist in orbit at the same time (different satellites and orbits permissible).

c) Total solar irradiance (TSI) and ultraviolet spectral irradiance are complementary. When one sees a variation in the total irradiance from the sun, much of that variation occurs in the ultraviolet. Hence, monitoring both the spectral and total distribution of solar radiation is valuable, one for energy input to the climate system, and the other for its impact on the absorption within the atmosphere and subsequent role in ozone production. There is, however, no requirement that these measurements be made from the same satellite or in the same orbit, but that they be in orbit at the same time. If the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) is lost, it has no impact on the total solar irradiance to be derived from ACRIM, for measurements from SOLSTICE are not required to interpret ACRIM observations.

1.3.2 Overlap strategy

The vast majority of EOS sensors, those that are used for long-term monitoring of climate parameters, require observations over a long period of time (e.g., 15+ years). This is generally beyond the scope of a single satellite/sensor system, thereby requiring multiple launches. The EOS observing strategy includes subsequent launches of similar sensors of potentially different optical and electronic design, and hence the long-term continuity of science results requires a minimum of a six-month period of overlap between subsequent launches of similar sensors. This overlap strategy assures an ability to intercompare the absolute calibration, performance, and idiosyncratic characteristics of subsequent observing systems.

In most cases, this observing strategy is highly desired in order to assure a long-term, high-quality, data set. For ACRIM measurements of TSI, however, it is an absolute requirement, since technology is beyond the capability of measuring absolute TSI to the required accuracy. Hence, in order to obtain a long-term data set over one or more solar cycles (11 years), it is necessary to have more than one TSI instrument, such as ACRIM, in orbit at the same time. Again, this does not require that they be on the same satellite or in the same orbit, but that a new satellite, with a replacement sensor, be launched before the failure of the replaced sensor.

1.3.3 Diurnal sampling

For ocean color and SST characterization, it is essential that well-calibrated data be available globally in order to quantify changes in the carbon uptake of the oceans during both El Niño and non-El Niño years. It is widely accepted by the Earth science community that uncertainties in cloud properties, especially their changes in response to a build up of carbon dioxide and other greenhouse gases in the Earth s atmosphere, are the largest source of uncertainty in current climate-model predictions of future climate response. Recent observations that the nighttime minimum temperature around the globe is increasing more rapidly than daytime maximum temperature seems to suggest changes are now occurring in global cloud cover, as other greenhouse gas explanations are unable to account for this behavior. A quantitative assessment of cloud properties (cloud droplet size, cloud height, etc.) requires a well-calibrated and continuous observing capability, coupled with advances in model development. Quantitative global observations are the greatest constraint on model parameterization and assumptions.

Unlike the ocean and atmosphere, the land surface is distinguished by high-spatial-frequency processes that require a high-spatial resolution to characterize. In particular, man-made changes (e.g., deforestation) are often initiated at scales requiring high resolution for early detection. The EOS satellites potentially offer the unique capability to seasonally monitor important small-scale processes on a global scale, viz, the inter- and intra-annual cycles of vegetation growth; deforestation; agricultural land use; erosion and other forms of land degradation; snow accumulation and melt and the associated freshwater reservoir replenishment; urbanization. The other systems affording global coverage do not provide the resolution to observe these processes in detail, and only the Landsat component of the EOS system provides a 20-year retrospective record of these processes.

To achieve a measurement strategy for highly-variable systems, most notably clouds and associated precipitation, EOS and partnering international space programs, include multiple satellites in orbit at one time or sometimes single spacecraft that are in mid-inclination and hence precessing orbits. An example of the latter is the TRMM satellite, launched in November 1997, that is in a 35˚-inclination orbit covering primarily tropical latitudes. The orbit of this satellite precesses in time so that a single area on the Earth's surface is observed at different times of day on subsequent days. This diurnal sampling strategy is also important for severe weather, such as hurricanes, floods, lightning, and tornadoes, and is a primary focus of geosynchronous observing systems. The loss of key observing capability or an entire satellite during the prime hurricane season in the fall has incalculable social costs.

1.3.4 Calibration requirements

Calibration is perhaps the most difficult EOS data continuity requirement to appreciate. The critical need to perform intra-system and intersystem data comparisons for global change research and monitoring justifies this requirement. In the future, EOS data will complement and add to the observations provided by systems of other agencies (e.g., NOAA, European Space Agency [ESA], National Space Development Agency of Japan [NASDA]) and will be compared to retrospective data acquired by earlier satellites, such as Landsat, the Earth Radiation Budget Satellite (ERBS), TOPEX/Poseidon, the Upper Atmosphere Research Satellite (UARS), the Solar Maximum Mission (SMM), and Nimbus-7. A lack of calibration would limit substantially the value of these comparisons. The situation is analogous to recording the height of a child with different sticks at different ages. If the different sticks are not calibrated in absolute units (e.g., in or cm), then we cannot infer the interannual growth rate of the child from stick-based measurements. Likewise, the reflected energy recorded by EOS sensors requires calibration in absolute units of energy. Otherwise, detecting and characterizing land-surface changes by comparing data from different sensors (e.g., MODIS to Landsat-7 data) becomes difficult, if not impossible. Similar examples can be found in such basic measurements as the energy output of the sun, Sea Surface Temperature (SST), total ozone content, energy balance of the Earth, ocean circulation, and global cloud cover.

Calibration will help prevent "apples-to-oranges" intercomparisons and analyses. Calibration will greatly enhance the role of EOS data to global-change research in the late 1990s and beyond. Without well-calibrated instruments it would not be possible to determine whether the ozone content of the Earth's atmosphere was decreasing over North America and Europe with any certainty, since it would also be possible that the satellite sensor had simply degraded. Without the ability to quantify such changes in the instrumentation, it would otherwise be impossible to ascribe changes to the global environment, whether due to humans or nature.

1.3.5 Continuity

The data continuity requirement does not mandate the cloning of the existing satellite systems. Only the scientifically essential capabilities of the EOS systems must be retained: i.e., the aforementioned repetitive, synoptic coverage, spectral coverage, appropriate spatial resolution, and calibration. These capabilities should be achieved by the most cost-effective and reliable technological approach available. Further, data continuity must not serve as a constraint on scientific and technologic advancements at any given time (i.e., not frozen in 1970s technology). System advancements that advance the role of EOS and enhance the value of the data (e.g., the addition of certain spectral bands that facilitate atmospheric correction) should be fostered and encouraged. Data continuity is not an excuse for technologic and scientific stagnation. The requirement is set forth only to ensure that the unique and critical role of EOS, as afforded by its scientifically essential capabilities, continues into the late 1990s and beyond.

Specific examples where calibration, validation, and continuity are vitally important are:

1) Radar altimetry of the oceans from Jason-1 will be used to assess seasonal-to-interdecadal changes of the ocean circulation. At these time scales the ocean is thought to play a major role in climate change through the transport of heat and exchange of heat with the atmosphere. Radar altimetry is the only way to obtain global measurements of the upper-ocean circulation to determine how and where the heat is moved. This information is required to improve forecasts of seasonal-to-interdecadal climate change.

2) Jason-1, AM-1, and PM-1 measurements will provide crucial information for modeling the ocean ecosystems, since ocean ecosystems are strongly influenced by the advection of nutrients and plankton communities. Understanding how these ecosystems change on seasonal-to-interdecadal time scales is a goal of EOS and can only be done with continuous observations of the ocean circulation.

3) At time scales less than a century, the ocean circulation is primarily driven by the force of the wind stress on the ocean surface. The lack of long-term accurate observations of the wind stress at the ocean surface has been a primary deterrent to improved forecasts of ocean-atmosphere climate phenomena, such as the El Niño. EOS will address this issue by providing long-term observations of the global wind stress on the ocean surface with SeaWinds, to be flown on QuikSCAT and the Japanese ADEOS II spacecraft.

4) The direct observation of global sea-level rise on seasonal-to-interdecadal time scales is a goal of Jason-1. This unique parameter provides a means to monitor changes in the global climate, such as global warming or cooling, changes in the water cycle, or tectonic changes in the shape of the Earth's surface. This measurement requires accuracy of 1 part in 10^9; long-term calibration of the altimeter system is essential to sort out instrument drift from geophysical signal.

5) The observations of the ocean circulation provided by Jason-1 will be used in global ocean models through data assimilation to improve our ability to forecast climate change. Data assimilation improves a model forecast through the use of direct observations. Assimilation requires knowledge of both the uncertainty in the observations and the model physics. Calibration of Jason-1 instruments is essential to quantify the error budget of the altimeter system for model assimilation and prediction. The goals of Jason-1 cannot be achieved without careful calibration of the instrument throughout the lifetime of the mission.

6) Satellite altimetry provides the only means of measuring the global ocean in a synoptic fashion, in order to understand the physics of ocean circulation. Calibrated, long-term measurements of the ocean circulation are needed to develop and validate climate prediction models with practical benefits for society that could be measured in trillions of dollars over the next century.

7) Long-term observations of the ocean circulation from Jason-1 are crucial for understanding the seasonal, interannual, and decade-to-century fluctuations in ocean circulation that are both responsible for, and indicative of, climate change. Thus, both climate prediction and climate monitoring are at stake.

8) A long-term fluctuation in global heat transport, such as into the N. Atlantic via a conveyor-belt circulation, would manifest itself in subtle changes of the time-mean-height differences across the Gulf Stream and connecting currents, as well as in changes in the eddy variability along the entire path of the great conveyor. Model simulations combined with long-term ocean-height measurements could lead to an advanced warning of the regional aspects of global warming.

9) The primary purpose of the GLAS laser altimeter is to determine on-going changes in ice-sheet volume and interannual and decadal changes in ice elevations that may be caused by changes in melting and pre-

cipitation in polar regions. The data are needed to predict sea-level rise during the next century. About five years of GLAS observations are required to determine the present-day rate of ice growth or shrinkage. Longer-term observations are needed to determine how the melting and precipitation forcings are changing as climate warming occurs, in order to confirm or revise predictions.

10) Sea ice is a major variable affecting the predicted amplification of the greenhouse warming in polar regions and the moisture available for changes in snowfall and ice-sheet mass balance. While twenty years of satellite passive microwave observations of sea-ice area have demonstrated that significant decadal-scale changes occur regionally, the overall hemispheric and global changes have been small. Nevertheless, problems remain in producing a uniform time series due to changes in the sensors, inadequate calibrations, and data gaps. For example, a new data gap would be assured if recorders on the Defense Meteorological Satellite Program (DMSP) satellite carrying SSM/I were to fail. With the data sets available, it has been very difficult to assess whether the overall sea-ice changes observed during the last twenty years are associated with changes in polar climate or are instrumental. AMSR-E on EOS PM-1 will provide a well-calibrated long-term data set of sea-ice extent and open water within the ice pack, as well as snow cover on land and the extent and duration of snow melting.

11) Clouds and changes in cloud cover have an enormous impact on climate change, since the longwave greenhouse effect of clouds is approximately seven times larger than that of doubling carbon dioxide. Thus a small change in cloud-top altitude, cloud thickness, cloud-droplet size or phase, or extent, can have a dramatic impact on the nighttime minimum and daytime maximum temperature at the Earth's surface under changing climate forcing conditions. Hence, a long-term, well-calibrated multispectral data set (such as that to be provided by MODIS on EOS AM-1 and PM-1) is necessary to quantify cloud properties in the Earth's atmosphere. In addition, the radiation response at the TOA and at the surface, to be provided by CERES, are necessary to constrain climate models and hence improve our confidence in their predictions.

12) SST can be monitored from space provided the calibration of the thermal infrared channels is well determined and stable. Stability is necessary to be able to ascribe long-term changes to the ocean surface rather than to the instrument. Quantitative radiometry is also required to make atmospheric corrections, whereby the effects of the intervening atmosphere (aerosols, water vapor) are removed from the spacecraft signal to infer the color and hence chlorophyll content of the oceans.

13) Long-term ozone trends, and atmospheric constituent changes that lead to ozone loss, can most readily be monitored from space using well-calibrated sensors. TOMS ozone measurements over many years (and now to be supplemented by OMI on the Chemistry mission) have been extremely valuable for long-term ozone-trend measurements. In addition, SAGE II (and later SAGE III) has been really vital in quantifying ozone trends due to its self-calibrating capability. The MLS sensor on EOS Chemistry will continue very exciting results obtained from UARS that show a high correlation between enhanced chlorine monoxide (ClO) levels and reduced ozone in the Antarctic polar vortex. Of perhaps more relevance to the public at large is the very large signature of high ClO in the Northern latitudes over North America and Europe. Monitoring ozone degradation, and subsequent recovery (following implementation of the Montreal protocol) requires continued measurements of both ozone and chemical species that affect ozone concentration, using well-calibrated sensors.

1.4 EOS contributions to national goals and needs

The USGCRP is placing increased emphasis on policy relevance in defining the breadth and focus of the national research efforts. End-to-end assessments (from the human and natural forcing factors to the human mitigation and adaptation response) are key requirements for national policy development. This refocusing of the USGCRP is prompting an examination of existing programs to determine if they are sufficiently policy-relevant and if they are responsive to national needs. Consequently, the USGCRP office and leading global change agencies developed a preliminary set of questions and products to assess the policy relevance of major USGCRP efforts.

Much of the research underway and planned as part of NASA's EOS is directed toward the highest priority elements of the USGCRP. EOS directly addresses national policy requirements for atmospheric ozone, natural variability and enhanced climate prediction, and long-term climate change. EOS also provides fundamental measures related to ecosystem change and aids in biodiversity research. Much of EOS research is a prerequisite for significant elements of the human dimensions research plan.

1.4.1 Atmospheric ozone and UV-B radiation

1.4.1.1 The national interest

The development of the Antarctic ozone hole and the global depletion of stratospheric ozone is well documented from satellite (Nimbus 7 SBUV, TOMS, Meteor TOMS, ADEOS TOMS, and NOAA SBUV) and in situ measurements. Ozone is a primary shield from harmful ultraviolet radiation and is a significant element of the global energy balance. The depletion of stratospheric ozone has been tied to two major causes. First, ozone depletion is clearly associated with a six-fold increase in stratospheric chlorine above natural levels, in large part due to the human emission of industrial chemicals such as chlorofluorocarbons. Second, volcanic emission of sulfur dioxide can lead to ozone depletion and increased annual variability. For example, the eruption of Mt. Pinatubo is correlated with a 35% reduction in stratospheric ozone at low Northern Hemisphere latitudes. Three additional factors may influence ozone chemistry: 1) ozone depletion can be caused by other radical species that are products of industrial emissions, 2) global warming may be a significant factor in ozone depletion because greenhouse gas warming leads to stratospheric cooling, enhancing the formation of polar stratospheric clouds that in turn trigger ozone-destroying chemical reactions, and 3) the emissions from high-altitude aircraft may also perturb stratospheric chemistry.

1.4.1.2 National policy requirements

The detection, causes, and impacts of significant changes in stratospheric ozone.

1.4.1.3 EOS policy-relevant contributions

EOS addresses the most important policy-relevant questions including the detection and prediction of ozone depletion, the isolation of human versus natural factors forcing changes in atmospheric ozone, the response of atmospheric ozone to human forcing, and an understanding of the uncertainties associated with ozone depletion and UV-B radiation.

1) What are the human and natural forcing agents in stratospheric ozone?

- HIRDLS, MLS, and SAGE III will monitor anthropogenic Cl and additional known threats from industrial chemicals including CFCs, other halogens (bromine-containing compounds), nitrogen compounds used both in agriculture and emitted directly by high-flying aircraft, and sulfur from stratospheric aircraft (leading to increased aerosols with resulting heterogeneous chemistry detrimental to ozone).

- The injected SO_2 from volcanic eruptions leads to more sulfate aerosols in the stratosphere, allowing enhanced heterogeneous chemistry (involving the industrial chlorine already in the stratosphere) detrimental to ozone. EOS will assess the role of volcanism in stratospheric chemistry through multiple measurements including: sulfate aerosols mapped and monitored by HIRDLS and SAGE III; total column abundance of aerosols measured with MODIS and MISR; volcanic gas (SO_2 and HCL) contributions measured with TES and MLS; and stratospheric sulfur dioxide monitored with TOMS and OMI. The chemical imprint of volcanoes will be directly tied to the latitude, season, and eruption characteristics of the volcanic eruptions.

- MOPITT will measure the concentration of CO, which is related to the tropospheric concentration of OH, and thus the indirect control of the amount of CH_4 and HCFCs that reach the stratosphere.

- AIRS and HIRDLS will provide an accurate record of natural temperature variations for the study of chemical reactions. SAGE III and HIRDLS will measure polar stratospheric clouds and temperatures (e.g., stratospheric warmings). These measurements will provide an understanding of the role of natural temperature changes in producing ozone variability and the potential determination of the role of global warming.

- MLS will contribute measurements that are not degraded by clouds or volcanic aerosols, allowing critical observations of important extreme events such as volcanic eruptions and that can be made in the presence of polar stratospheric clouds.

- The long-term measurements of ozone and other critical gases, temperatures, and aerosols provided by EOS and other sources is critical to separate natural variations and human-induced ozone depletion.

2) *What has been and will be the response of atmospheric ozone and UV-B radiation to human forcing?*

- HIRDLS and MLS data products make essential contributions to detecting ozone depletion agents including: ClO, BrO, OH, NO, NO_2 (chemical radicals); H_2O_5, $CLONO_2$, HCl, HNO_3 (chemical reservoirs); H_2O, N_2O, CH_4, F11, F12 (source gases); SO_2 (volcanic injections). These species define the chemical cycles that destroy ozone. The measurements will be continuously made from the upper troposphere through the mesosphere at high horizontal and vertical resolution. The instruments are sufficiently stable to detect 1% changes. Daily three-dimensional fields of all parameters are produced.

- SAGE III and HIRDLS will measure stratospheric ozone, as well as NO_2, NO_3, OClO, H_2O, polar stratospheric clouds, temperature, and aerosols. EOS will provide 1-km vertical resolution, with excellent long-term precision, providing critical profile data needed to understand processes required to develop predictive models.

- AIRS/AMSU will measure the vertical distribution of ozone in the troposphere and the stratosphere in five layers twice daily globally with an accuracy of 10% and will determine the total column with an accuracy of 3%, which can provide a backup for the TOMS and OMI instruments.

- MODIS will measure total column ozone twice daily with 10-20% accuracy, which can provide backup for the more-accurate TOMS and OMI instruments.

- EOS investigators will produce long-term calibrated data sets based on intercomparison studies including earlier Nimbus 7 SBUV, TOMS, Meteor TOMS, ADEOS TOMS, and NOAA SBUV/2 measurements. The ozone-mapping instruments on the European Remote-Sensing Satellite-2 (ERS-2) and the Environmental Satellite, ESA (ENVISAT) will provide additional calibrated data sets.

- EOS global vertical sounding capability of the primary radicals, reservoirs, and source gases in the stratospheric chemical cycle and EOS aerosol measurements, in conjunction with existing capabilities with TOMS, provide considerable opportunity to develop predictive and diagnostic models for ozone depletion and UV-B radiation. EOS investigators will develop 3-dimensional chemical transport models of the stratosphere, in predictive and diagnostic modes, which can be utilized to calculate radical trace-gas concentrations, estimate ozone losses, and calculate the UV-B flux.

3) *What are the uncertainties and what is the potential for change?*

- EOS vertical profiles (MLS, HIRDLS and SAGE III) address major uncertainties in understanding stratospheric chemistry.

- HIRDLS will provide daily measurements of the location and extent of polar stratospheric clouds on which chlorine is transformed into active forms.

- Ozone decreases that may occur in response to the unprecedented high chlorine abundances expected during the next decade and to additional trace gases emitted by humans are not known. MLS and HIRDLS, by continuously monitoring the key radicals that destroy ozone, provide a capability for the earliest-possible detection of potential ozone depletion even by yet undiscovered processes for enhancing the role of human-produced chemical radicals.

- EOS measurements, including stratospheric temperatures (AIRS, HIRDLS, MLS, and SAGE III) will increase our understanding of the potential ozone decrease in response to the stratospheric cooling caused by increasing atmospheric CO_2.

- EOS monitoring of clouds and the radiant energy budget will provide a diagnostic measure of the UV-B transmission that is cloud dependent. CERES, AIRS, MODIS, and MISR will produce cloud-forcing products and cloud-radiative properties useful for UV-B analysis.

- EOS will monitor volcanic eruptions and their impact as a major cause of natural variability in ozone chemistry and enhancement of the human forcing on ozone depletion.

- EOS will be able to contribute to the assessment of the impact of ozone depletion and associated increases in UV-B through comparisons with MODIS primary productivity measurements.

1.4.2 Natural variability and enhanced climate prediction

1.4.2.1 The national interest

The skillful prediction, months to years in advance, of precipitation and temperature can yield increased agricultural and forestry production and distribution, improved hydroelectric power planning and utilization, and more-effective responses to floods and droughts and better management planning. The goal is the utilization of short-term (seasonal and interannual) climate forecasting for social and economic benefit. Predictability has already been demonstrated for some aspects of the climate system, particularly for El Niño. Further, short-term climate forecasting, which requires a comprehensive knowledge of the atmospheric circulation and its interaction with the ocean and the land surface, contributes substantially to the predictions of long-term greenhouse warming. Short-term climate forecasts can be validated and verified and the economic benefits can be directly proven. Many of the challenges inherent to long-term prediction can be met on seasonal-to-interannual time scales. Finally, detection of long-term human-induced climate change requires an understanding of natural variability.

1.4.2.2 National policy requirements

1) Operational predictions one year ahead of interannual climate fluctuations.

2) Detection, causes, and impacts of natural decadal climate variations.

1.4.2.3 EOS policy-relevant contributions

EOS will help define the natural and human factors that influence seasonal-to-interannual climate. A significant fraction of natural climate variability is governed by modification of the atmosphere by global SST, by variations in land moisture, vegetation, and snow- and sea-ice cover globally. Additional variability is introduced from solar variability, longer-term anomalies, and volcanic eruptions. Human-induced modifications of atmospheric chemistry may alter the nature of seasonal-to-interannual variability. The EOS contributions to understanding climate variability will enhance the ability to predict climatic change and variability from seasons to decades in advance.

1) *What are the natural and human factors that affect the seasonal-to-interannual climate and its anomalies?*

- EOS investigators will contribute substantially to the understanding of ocean-atmosphere interactions. Investigators will be able to combine altimetry (TOPEX/Poseidon, ERS-1, ERS-2, Jason-1), scatterometry (NSCAT, SeaWinds), ocean color (MODIS, SeaWiFS), and SST measurements (MODIS, AIRS, AMSR-E), assimilate these observations into forecasting models and resolve major characteristics of the surface oceans responsible for natural variability. These observations, with the temperature and humidity measurements of AIRS/AMSU and the cloud-radiation budgets from CERES, will allow investigators to connect SST variations with the large-scale and mesoscale circulation and improve boundary layer models that describe air-sea interaction. Global assimilation schemes will provide operational products necessary for predictions of interannual fluctuations and will also contribute to our understanding of the coupled ocean-atmosphere interactions and the prediction of phenomena such as El Niño.

- EOS measurements of snow cover, sea ice, surface temperature, land cover, vegetation characteristics and related parameters (e.g., fraction of photosynthetically-absorbed radiation), surface albedo, atmospheric temperature and humidity and radiative fluxes (ASTER, MODIS, MISR, CERES, AIRS, AMSR-E) will be essential to initialize, validate, and verify climate models designed to assess the role of the land surface in governing seasonal-to-interannual variability at regional-to-global scales. EOS measurements will provide substantial improvements in comparison with existing capabilities (e.g., the Advanced Very High-Resolution Radiometer [AVHRR]). Measurements of polar surface temperature, albedo, and sea-ice concentration will test climate model predictions of accelerated "greenhouse" warming in polar regions.

- EOS will be able to track and characterize emissions from volcanic eruptions that produce climatic variability on time scales of seasons to years. MISR and ASTER can track the height of plumes, MODIS and MISR the dispersal of the particulates, TOMS, OMI, TES, and MLS the dispersal of SO_2, and MISR, HIRDLS, and SAGE III the dispersal of stratospheric sulfate aerosols and the evolution of their vertical profiles. MODIS and MISR can provide a high-resolution view of the spatial distribution of stratospheric aerosols, and data from SAGE III, MODIS, and MISR can be used to monitor the evolution of the size of these aerosols.

- EOS will be able to characterize the abundance and properties of natural and human-made tropospheric aerosols that may change the effect of greenhouse gases on climate. MODIS, MISR, and EOSP will detect regional and global changes of aerosol distribution and variability of their size. They will be able to track several sources of aerosol (e.g., MODIS observations of fires as a source of biomass burning aerosol). EOSP will also determine the aerosol refractive index, a measure of the aerosol composition. Wind-blown dust from arid regions will be monitored for major source regions. SAGE III will increase our understanding of aerosol loading and removal.

- EOS (CERES, MODIS, AIRS, AMSR-E, and MISR) will provide a strong basis for monitoring variability in cloud properties (amount, type, liquid water content) which can both regulate climatic variability and define trends. Even 1-to-2% changes in cloud properties may be significant.

- ACRIM will provide systematic monitoring of TSI variations, which are essential to separate anthropogenic forcing from natural variations.

- SAGE III, HIRDLS, and MLS contribute observations to assess the interannual variability of radiatively-active gases (ozone, CH_4, F11, F12, nitrous oxides, water vapor) which may impact climate variability.

- The ability of EOS to monitor land-surface energy and moisture fluxes (particularly soil moisture) using a new generation of spatially-distributed hydrologic models (based on MODIS, ASTER, AIRS, AMSR-E, and other satellite data) will help us to better understand land-atmosphere climate interactions.

- EOS regional assessments provide baselines for determining changes in variability through monitoring of hydrologic parameters (precipitation, evaporation, water vapor, stream flows, glaciers, and snow cover) sensitive to climate change and through incorporation of historical observations.

2) *What is the ability to predict climatic anomalies a season in advance and what is the mechanism for verifying, distributing, and using these results? One-to-two years in advance?*

- EOS may not directly provide operational products that are predictions for a season or one-to-two years in advance; however, the entire suite of observations that define the characteristics of the surface (SSTs, land cover, (including snow), and sea ice) will provide important boundary conditions for predictions. The accuracy of these forecasts will likely depend on the accuracy with which we can measure the global state of the Earth system.

- Global-scale, near-real-time documentation of anomalies in regional precipitation-evaporation, snow cover, sea ice, and cloud cover will be of major value in climate forecasting.

- EOS will provide critical process information on air-sea interaction and cloud-climate interactions, which are major limitations in current climate forecasts and coupled atmosphere-ocean-land-ice climate models.

- EOS observations from the full suite of surface and sounding sensors (particularly for temperature, humidity, clouds, and radiation) and 4-D assimilation efforts will contribute to forecast validation.

- EOS monitoring of volcanic eruptions and their characteristics (aerosol loading and release of gases) will provide significant data for determination of climate anomalies.

- MODIS, through its capability to monitor the extent and vigor of vegetation, will provide short-term predictive capability for drought monitoring in semi-arid environments.

- EOS altimeter and scatterometer measurements, coupled with in situ measurements from the World Ocean Circulation Experiment (WOCE) campaigns, will allow an improved understanding of the three-dimensional general ocean circulation and its influences on global change. These data and the associated understanding will aid the development of requisite models for making long-term predictions.

1.4.3 Long-term climate change including global warming

1.4.3.1 The national interest

Human activities are leading to changes in the land surface and the composition of the atmosphere with significant potential to cause decadal climate change. The alteration of the land surface modifies the energy-water-vegetation interaction at the land-atmosphere interface. Physically-based models indicate that changes in the surface energy and moisture budgets can have a significant impact on regional climates. Increases in carbon dioxide and other greenhouse gases influence the global energy budget promoting global warming and related climate changes. The detection of global warming is the subject of considerable debate, as the observing system in place over the last 100 years is inadequate to isolate long-term natural variability from human-induced change and lacks the capability to determine small changes in global temperature. Consequently, an assessment of global warming is dependent on the predictions of climate models. State-of-the-art general circulation models (GCMs) predict a global warming of between 1.5˚ and 4.5˚C and substantial changes in precipitation and evaporation for a doubling of the atmospheric carbon dioxide concentration over its pre-industrial value. Improved estimates of mean sea-level change, on both local and global scales, as a means of detecting the consequences of greenhouse gas-induced global warming, is an important adjunct requirement. A climate change of this magnitude will have significant impact on energy utilization, agriculture (drought and floods), natural ecosystems, water resource availability, water quality, and potentially, sea level. However, the potential impact is very different for a 1.5˚C warming as opposed to a 4.5˚C warming. The magnitude and rate of global climate change control the potential impact on society.

1.4.3.2 National policy requirements

1) Plausible scenarios for regional climate and ecosystem change, suitable for impact analysis.

2) Improved estimates of the relative global-warming potential for various gases and aerosols, including their interactions and indirect effects of other chemical species.

3) Improved ability to determine the regional sources and sinks for atmospheric carbon dioxide, as part of the monitoring system for greenhouse-gas emissions-reduction agreement.

4) Reduction in the range of predictions of the rate and magnitude of global warming over the next century (through reductions in the uncertainties of cloud-climate interactions and ocean heat storage).

5) Predictions of anthropogenic interdecadal changes in regional climate, in the context of natural variability.

6) Detection, beyond reasonable doubt, of greenhouse-gas-induced global warming, and documentation of other climatically-significant changes in the global environment.

7) Improved understanding of the interactions of human societies with the global environment, enabling quantitative analyses of existing and anticipated patterns of change.

1.4.3.3 EOS policy-relevant contributions

The detection of climate change, the reduction in the uncertainty associated with climate change, the improvement of estimates of global warming potential and sources and sinks of greenhouse gases, and improved prediction of regional change, including natural variability, depend on: 1) an adequate monitoring capability, 2) improved knowledge of the forcing factors, 3) improved predictive capability to determine the response of the climate system, and 4) an assessment of the uncertainties. EOS contributes to each of these fundamental components required to serve national policy requirements. The synergy between many observations and many investigators will allow EOS to contribute to the understanding of the more-complex, yet essential, Earth processes, such as the hydrologic cycle.

1) What are the human-induced and natural forcing changes in the global system and climate?

- MODIS, ASTER, and MISR will characterize changes in land-surface cover and surface vegetation, with the capability of providing long-term monitoring. EOS will provide surface fluxes of energy and carbon with unprecedented accuracy and spatial resolution. In conjunction with historical observations, the human alteration of the landscape can be mapped and utilized to determine the potential impact on climate.

- AIRS/AMSU/HSB will determine the three-dimensional structure of moisture in the troposphere and stratosphere and will measure the spectral changes in the longwave radiation going to space, which are needed to monitor the effects of trace gases on global warming.

- EOS will assess the role of volcanism as a natural forcing factor in the global system. Sulfate aerosols will be mapped and monitored with SAGE III; total column abundance of aerosols will be measured with MODIS and MISR; volcanic gases can be measured with TES, OMI, and MLS. The role of volcanism versus human-induced aerosol loading can be deciphered based on the chemical imprint of volcanoes, monitoring of volcanic eruptions, and examining trends in aerosol loading.

- MODIS, MISR, and EOSP will detect regional and global changes in tropospheric aerosols.

- Jason-1 and other precursor altimeter missions will provide a well-calibrated long-term measurement of absolute sea level. The accurate monitoring and prediction of the mean sea level on a global basis provides a means of detecting the effects of greenhouse-gas-induced global warming. The accurate prediction of sea-level rise could have significant economic and societal impacts.

- MOPITT and TES will measure CO and CH_4, and TES will measure H_2O, O_3, and N_2O, all of which are needed to begin to separate human and natural greenhouse forcing.

- MODIS measures of biomass burning will contribute to knowledge of trace-gas emissions.

- ACRIM will measure total solar irradiance, a fundamental measure of solar variability, which is needed to separate human and natural greenhouse forcing. SOLSTICE will measure the total variation of UV and its contribution to the natural variability of ozone.

- EOS measures of ozone depletion will define the abundances and trends of this radiatively-important gas.

- EOS investigators will complete extensive model experimentation aimed at quantitative comparison of the different human-induced and natural forcing changes. These sensitivity experiments will be completed at both regional and global scales.

2) *What has been and will be the response of the climate system to human forcing?*

- The response of the climate system will be defined by modeling efforts of EOS investigators based on a quantitative understanding of the natural and anthropogenic forcing from aerosols (MISR, SAGE III, EOSP, MODIS, HIRDLS), solar irradiance variations (ACRIM TSI), land-surface changes (MISR, MODIS, ASTER), and radiatively-important gases measured by EOS (H_2O, CH_4, O_3, CH_4, N_2O, F11, F12), and from other sources (CO_2). EOS provides an unprecedented opportunity to assess the response of the climate system based on the full spectrum of forcing factors.

- The characterization of clouds (CERES, MODIS, ASTER, MISR, AIRS), the radiation balance (CERES), temperature and humidity (MODIS, AIRS/AMSU/HSB), winds (SeaWinds, Jason-1), and ice and snow cover (AMSR-E, MISR, MODIS) provide a unique capability to validate model predictions.

- EOS will provide significant opportunities to document surface fluxes of energy and moisture over the land surface and the oceans, to document regional and global radiation budgets required to understand cloud-climate feedbacks, and to determine ocean heat transport. EOS will provide the first satellite-based opportunity to examine ice-sheet mass balance. These elements encompass major limitations in current climate models, and thus EOS will contribute substantially to the improved prediction of regional and global climate change in the next generation of climate models.

- EOS investigators will utilize improved measurements of surface fluxes and clouds and radiation to develop high-resolution model predictions suitable for regional prediction of climate change.

3) *How do human-induced changes compare to variations and changes in the natural system? Can these changes be detected and modeled?*

- Natural variability of the climate system will be better defined through EOS observations of the temporal and spatial variability of aerosols, vegetation, sea ice, snow cover, temperature, water vapor, ozone, and clouds. EOS will assess variability due to cloud interactions, vegetation and other surface changes, carbon/trace-gas perturbations, and the major climate forcing factors. MISR bi-directional reflectance measurements will distinguish between natural or human-induced land-surface cover and surface albedo variations, related to desertification, irrigation, deforestation, and urbanization. Characterization of aerosol characteristics (abundance, particle sizes, albedo, optical thickness) with MISR, MODIS, and EOSP, in conjunction with cloud measures, can be used to determine the indirect effect of aerosols as cloud-condensation nuclei to define the climate impact of aerosols, including their interactions. Measures of CO and CH_4 assist in the direct measurement of potential global warming.

- EOS 4-D assimilation models will provide a physically-consistent global measure of climate change.

- EOS investigators will apply these satellite observations to assess the role of aerosol loading of the atmosphere in possible mitigation of global warming due to increased greenhouse-gas concentrations. The monitoring of aerosols, cloud properties, ozone, and water vapor will provide a basis for improved estimates of the relative global-warming potential of various gases and aerosols, including interactions and indirect effects.

- The determination of the carbon balance of terrestrial ecosystems from satellites for different regions and resolutions will yield scenarios for fluxes under different climate conditions or land-management conditions. Terrestrial vegetation characteristics and ocean productivity measures will aid in the determination of regional sources and sinks for atmospheric CO_2, N_2O, and CH_4.

- Multi-decadal regional historical studies will provide an important perspective on the impact of human-induced-versus-natural variations.

- Improvements to climate models based on EOS observations and study will contribute to the development of more-realistic simulations of future climate. These model predictions can be verified by long-term observations or can provide estimates of the statistical likelihood of change.

- Measurement of the major climate forcing factors by EOS is a prerequisite for detection of human-induced global change beyond reasonable doubt.

- The long-term measurements of water vapor, atmospheric temperature, cloud properties, and SST (AIRS/AMSU/HSB, MODIS, CERES) are essential to detection of global change.

- HIRDLS will measure stratospheric cooling, a major expected signal of greenhouse warming.

4) *What are the uncertainties and what is the potential for surprises, including sudden changes in the frequency and intensity of extreme events?*

- Uncertainties in cloud-climate feedbacks are regarded as one of the most important limitations of current models. The unparalleled measurements of clouds, cloud radiation, and water vapor will allow EOS investigators to incorporate much-improved parameterizations in climate models.

- EOS observations of surface temperatures, atmospheric temperatures and moisture, surface characteristics, and winds will provide major opportunities to address the uncertainties associated with the fluxes of moisture and energy at the land-atmosphere and ocean-atmosphere interfaces and their parameterization in climate models.

- Synergistic measurements of temperature and humidity with ocean altimetry and scatterometry will provide a unique opportunity to improve estimates of ocean heat transport, a major uncertainty in our knowledge of the climate system.

- Current observations are inadequate to determine if the major ice sheets are growing or shrinking. The GLAS instrument will provide the first satellite-based opportunity to address this major uncertainty.

- EOS monitoring of key climate quantities (e.g., SSTs, atmospheric temperature and moisture, clouds, radiation, and sea level) will be utilized to improve climate models and examine climate trends.

- EOS plans to monitor the major climatic forcing factors (aerosols, radiatively active gases, solar irradiance, land cover change), which are critical to limiting the uncertainties in climate predictions.

- The location, duration, and type of activity associated with large volcanic eruptions, a major source of uncertainty, will be monitored by EOS.

- Models developed by EOS investigators provide one of the few opportunities to address the potential of changes in the frequency and magnitude of extreme events, and will also contribute to understanding of the frequency and intensity of other phenomena such as El Niño.

- Historical and pre-historical examinations of specific regions by EOS investigators will provide information on the frequency of extreme events and potential thresholds for their occurrence.

1.4.4 Ecosystem change and biodiversity

1.4.4.1 The national interest

The prevention of dramatic human-induced loss of species is a major responsibility, both from the view of species as natural resources and from our obligations for global stewardship. The loss of biodiversity will influence ecosystem function, including predation and dominance. Land use introduces patchiness or large-scale changes in habitats, modifying ecosystem function, including extinction, migration pathways, and survival. Land-use management may also be guided by the potential impact of utilization on carbon and nitrogen budgets. The record from Earth history indicates dramatic expansion and contraction of habitats in response to past global climate changes. Today, human activities play a considerable role in aiding or hindering habitat response to global change. Climate change will influence both the distribution of habitats and the patterns of land use. Changes in atmospheric chemistry will also influence ecosystem response. Ozone depletion and increased UV-B introduce the potential for ecosystem damage as well as human health issues. Sea-level increases in response to global warming will introduce considerable dislocations of estuaries, marshes, and near-shore ecosystems.

1.4.4.2 National policy requirements

The detection of significant changes in ecosystems and biodiversity, and determination of the response of ecosystems and biodiversity to the changes in atmospheric composition, UV-B, land use, climate, and sea level.

1.4.4.3 EOS Policy-Relevant Contributions

The EOS will specifically map changes in land-use patterns, vegetation type, and photosynthetic activity, which will provide a foundation for ecosystem response models based on habitat scale and patchiness. EOS investigators will help produce better climate-change predictions which can be utilized to investigate ecosystem response in both terrestrial and oceanic realms. EOS models of carbon and nitrogen balance will aid in the assessment of the impact of land use and global-change-induced habitat changes. EOS instruments will provide the basis for detecting trends in ecosystems as a function of changes in atmospheric chemistry. EOS will also monitor volcanic eruptions as a natural disruptive force for ecosystems.

1) *What have been and will be the impacts of global change on terrestrial systems and their wildlife, including forests, grasslands, arid lands, the tropics, and high latitudes?*

- MODIS, ASTER, MISR and Landsat will map changes in land-cover patterns, including expansion and contraction of farmland, urban growth, deforestation, and forest regrowth. These changes in pattern can be related to land use or environmental change. EOS will provide essential databases on grasslands, tundra, forests, and tropical deforestation which will be a basis for ecosystem response studies.

- MODIS and MISR will produce measures of leaf area index (LAI) and the fraction of absorbed photosynthetically-active radiation, which can provide estimates of changes in net primary productivity.

- EOS instruments and models will be able to examine changes in carbon, NPP, and nitrogen balances and will be able to assess the impact of ecosystem disturbances on the carbon pool. EOS models will examine the potential of increased sequestration of CO_2 through forest management and practices.

- EOS will provide the basis to detect trends related to increased carbon dioxide and ozone depletion.

- EOS will produce climate predictions at global and regional scales in response to the full spectrum of climatic forcing factors (including land use) and will work to substantially improve climate models by addressing their major limitations with EOS observations. These predictions will be the basis to assess climate impacts on ecosystems, including potential biome shifts in response to global climate change.

- EOS investigators will use regional studies to examine past interdecadal variations in climate and biome distribution to analyze ecosystem response to climate change.

- MODIS, ASTER, MISR, and Landsat will monitor the role of volcanism in ecosystem impact.

- MODIS observation of fires adds an important capability to assess biomass burning, an agent of ecosystem change.

2) *What have been and will be the impacts of global change on coastal and marine ecosystems?*

- EOS investigators will develop biophysical models of the ocean circulation and productivity that can be utilized to examine the response to forcing factors such as changing wind stress, air/sea fluxes, and incident solar energy.

- MODIS will examine coastal and marine ocean color, providing data on the impact of global change on ecosystems, and providing fundamental information on natural variability.

- GLAS and Jason-1 will assess the mass balance of the ice sheets and mean sea-level change, providing key observations for potential impacts in coastal regions.

- EOS observations in conjunction with models of the ocean circulation will examine the impact of wind forcing on coastal circulation, including the impact on fisheries.

3) *What have been and will be the impacts of global change on biodiversity?*

- Through maps of vegetation-cover change and habitat type and extent, EOS observations can be utilized to assess potential changes in biodiversity through the use of ecosystem models.

4) *What are the uncertainties and the potential for surprises and unexpected changes in the global ecosystem?*

- Through data-constrained simulation models of the carbon and nitrogen balance, EOS investigators will be able to examine the sensitivity of ecosystems to global change.

- EOS will provide extensive climate-model-sensitivity experiments for the full host of climate forcing factors at global-to-regional scales. These climate predictions are a prerequisite for assessing uncertainties and potential for surprises associated with ecosystem response to climate change.

1.4.5 Human dimensions and economics

1.4.5.1 The national interest

The potential magnitude of global change introduces the need to define strategies for mitigation or adaptation. The strategies for mitigation and adaptation may have widely different economic and societal impact involving health, standard of living, and quality of life. Knowledge of the rate and magnitude of global change and its impact at global and regional scales is essential to assess social and economic impact. Even moderate climate change may result in significant changes in the distribution and availability of critical resources such as water. We must be able to understand the nature of the human forcing of global change, particularly land and energy use. Human behavior, including valuation of the environment, issues of intergenerational equity, global-change decision making and the role of institutions become essential elements of assessing the human dimension of global change. Without these foundations, the strategies for mitigation or adaptation may be misguided, resulting in either inadequate or unnecessary policies.

1.4.5.2 National policy requirements

Definition of the interactions of global change with the major areas of societal activity and development of rational adaptation and mitigation strategies.

1.4.5.3 EOS policy-relevant contributions

EOS addresses natural hazards such as volcanism, but most importantly provides a realistic basis for understanding the potential rate and magnitude of global change. EOS studies will define the vulnerabilities of water resources, agriculture, and ecosystems to climate change. EOS will provide fundamental data sets on land-cover change, clearly addressing the need to understand one of the most significant human forcing factors of global change. EOS will also provide fundamental measures of sea-level change, a major factor in coastal regions.

1) *What are the interactions with agriculture?*

- MISR, ASTER, and MODIS will assess changes in land cover, surface albedo, biomass burning, and productivity as a basis to assess human activity and to define the interactions between climate and agriculture.

- EOS temperature and humidity observations (AIRS/AMSU/HSB) and regional and global climate change predictions from EOS investigators will be the basis for determining potential changes in agricultural yields, agricultural management practices, and implications for land use.

- The EOS focus on radiatively-important gases from agriculture may influence management practice.

- A determination of the potential for volcanic eruptions may lead to agricultural risk evaluation.

2) What are the interactions with freshwater resources?

- EOS monitoring of snow cover and glaciers at a regional and hemispheric level (MODIS, AMSR-E) provides a basis for short-term assessment of a significant water-resource component. GLAS will measure global ice-sheet mass balance.

- EOS climate predictions at global and regional scales will emphasize the water balance and its sensitivity to global change, meeting a major requirement to assess water-resource vulnerability to global change.

3) What are the interactions in the coastal zone and marginal sea-ice zone, including fisheries?

- High-resolution coastal-circulation studies, including biology, will provide important data on primary productivity, a key element in fisheries.

4) What are the interactions with human health, including disease vectors, air quality, and UV-B radiation?

- TES, MISR, ASTER, and MODIS will monitor volcanic gas hazards in association with major eruptions, which have the potential of human impact.

- MLS, HIRDLS, and SAGE III will provide diagnostic information on ozone depletion by monitoring enhancements in precursor chemical radicals. This gives the capability for providing early warning potentials for increased UV-B.

- TES and MOPITT will provide a large number of measurements (O_3, CO, CH_4, NO, NO_2, and HNO_3) which will greatly aid our understanding of the chemistry of the troposphere.

5) What are the interactions with land use, including soils and erosion?

- EOS instruments will provide unprecedented measurements of the scale and magnitude of changes in land cover associated with land-use change.

6) What are the interactions with business and commerce?

- MODIS, ASTER, MISR, and Landsat will assess volcanic hazards, both on the ground and in the air, with implications for the destruction of regional commerce and disruption of aircraft flight patterns.

- EOS predictions of climate change at global-to-regional scales will have substantial impacts on business and commerce through implications of climate change for agriculture and water-resource availability.

7) What are the uncertainties and what is the potential for surprises?

- Without a full examination of the potential impact of climate change and human-induced modifications to land cover, we will be unable to determine important potential societal impacts of global change.

1.5 Summary

NASA's EOS was designed to initiate a new era of integrated global observations intended to advance our understanding of the entire Earth System on a global scale through developing a deeper understanding of the components of that system, their interactions, and how the Earth is changing. The global homogeneous long-term measurements of the Earth 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 we can expect significant enhancements in our ability to understand and predict global changes and their effects on human activities.

EOS will provide an unparalleled opportunity for long-term observation and monitoring of key variables such as total solar irradiance, radiative energy fluxes, cloud properties, aerosols, atmospheric chemistry, ice-sheet mass balance, land-surface characteristics, and precipitation. It will also provide improved understanding of the processes that relate different components of the Earth system. For example, EOS will address key priorities of the USGCRP, such as the relationship between clouds and water vapor to global climate and their effects on climate sensitivity, while also providing a more-accurate treatment of clouds and water vapor and their radiative effects in global climate models. There will be better measurements of surface characteristics, energy fluxes, and precipitation, and consequent improved understanding of the processes that connect atmospheric and surface processes and hence more-accurate parameterizations in global-climate models. Improvements in observational knowledge and understanding of the processes that couple the atmosphere-land-vegetation systems and the atmosphere-ocean system will result in substantial improvements in our understanding and simulation of land surface and oceanic processes, and in the development of global climate models.

In this manner, EOS plays a critical role 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.

Chapter 1 Index