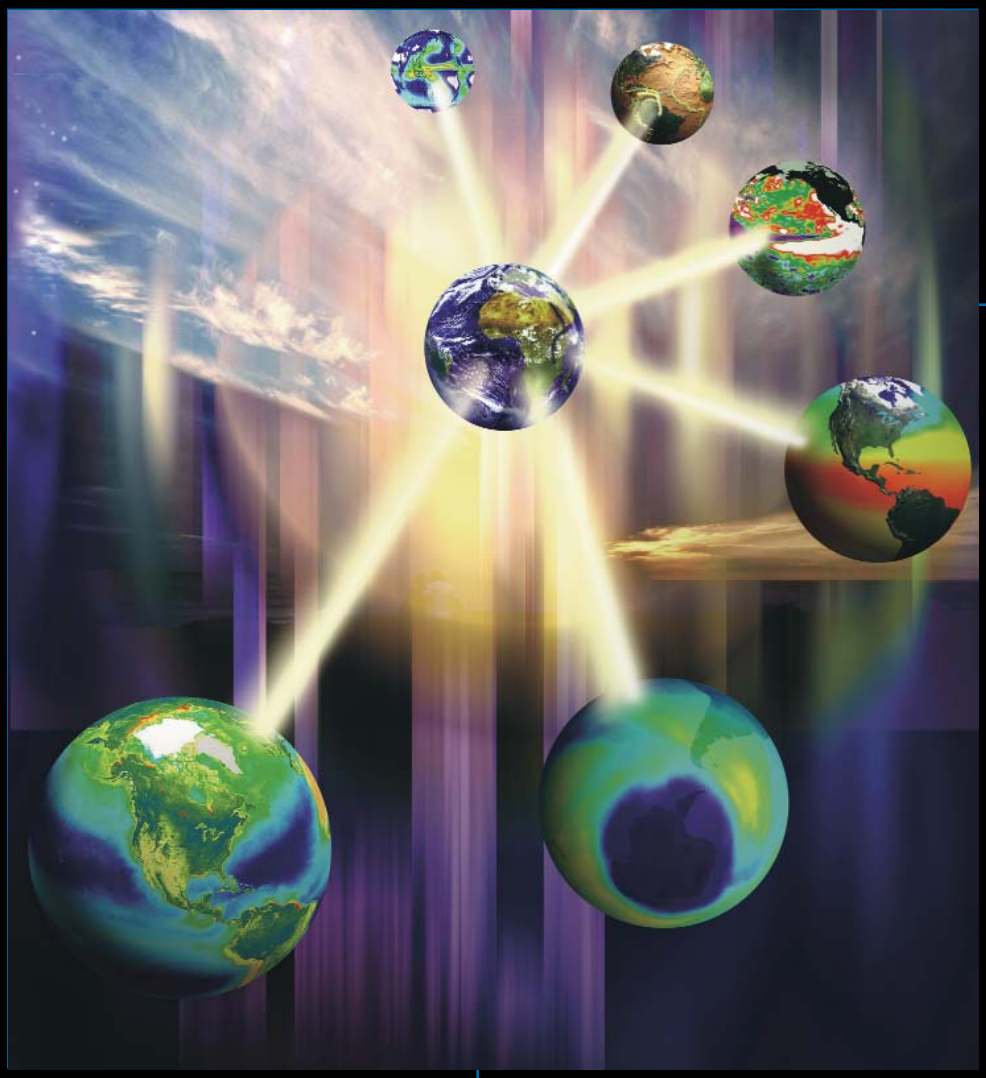


National Aeronautics and Space Administration

Earth Science Research Plan

1/6/05 DRAFT

Preface

This Research Plan is one of five documents that expand the broad strategy for Earth science within the U.S. National Aeronautics and Space Administration (NASA) into research, technology, data and information management, applications, and education. Prepared in consultation with NASA's Earth System Science and Applications Advisory Committee (ESSAAC) and with contributions by numerous investigators working at NASA centers, universities, and other institutions, this research plan updates and revises the Earth Science Enterprise Research Strategy published in December 2000.

Meant to define and explain Earth science research within NASA as part of the Agency's Earth Science Enterprise Strategy published in October 2003, this Research Plan was undergoing final revisions when in July 2004 NASA announced an agency-wide transformation that establishrd a consolidated Science Mission Directorate with an Earth-Sun System Division. In its current version, the document provides a baseline and point of departure for further strategic planning within the Science Mission Directorate.

In keeping with a continuing commitment to Earth science through the 2004 transformation, one of NASA's newly stated objectives is to:

> *Conduct a program of research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems.*

A strategic roadmapping effort within NASA is outlining multi-decadal pathways for each of the Agency's strategic objectives. In addition, NASA has asked the U.S. National Research Council to conduct a decadal survey of scientific priorities for Earth observations from space. This updated Research Plan describes the intellectual context and content of today's program and NASA's plans through the end of this decade. It thus provides a foundation on which the Agency roadmapping and NRC Decadal Survey efforts can plan for the decades beyond. As the products of those efforts will doubtless have implications for choices in this decade, NASA envisions an iterative relationship between those products and this document.

NASA Earth Science Research Plan

1 Introduction 1
1.1 NASA Earth Science Plans. 2

2 Approach to Earth System Science 5
2.1 Research Focus Areas 5
2.1.1 Climate Variability and Change 9
2.1.2 Atmospheric Composition 11
2.1.3 Carbon Cycle and Ecosystems 13
2.1.4 Water and Energy Cycle. 15
2.1.5 Weather . . 17
2.1.6 Earth Surface and Interior 19
2.2 Observations . . 21
2.2.1 Research and Development for Earth Observation Technology 22
2.2.2 Satellite Missions 22
2.2.3 Suborbital and Surface Observations 24
2.2.4 Systematic Earth Observing Systems and Data Records 25
2.3 Modeling, Analysis, and Prediction 25
2.3.1 Exploring Interactions within the Earth System 27
2.3.2 Distinguishing Natural from Human-Induced Change 27
2.3.3 Understanding and Predicting the Consequences of Earth System Change 29
2.3.4 Modeling Resources 30

3 Resources 33
3.1 NASA Research and Space Flight Centers 33
3.2 Extramural Investigators. 33
3.3 High-Performance Computing 34
3.4 Data and Information Systems 35

4 Implementation 36
4.1 Criteria for Evaluating Priorities. 36
4.1.1 Scientific Return. 37
4.1.2 Benefit to Society 37
4.1.3 Mandated Programs 37
4.1.4 Appropriate for NASA. 37
4.1.5 Partnership Opportunity 38
4.1.6 Technology Readiness 39
4.1.7 Program Balance 39
4.1.8 Cost/Budget Context 39
4.2 National and International Planning Coordination, and Collaboration 39

5 Integration and Synthesis . . 41

Appendices 48

1 Introduction

1 Introduction

The NASA vision is—
To improve life here
To extend life to there
To find life beyond

The NASA mission is—
To understand and protect our home planet
To explore the Universe and search for life
To inspire the next generation of explorers
…as only NASA can.

NASA's Earth science programs are essential to the implementation of three major Presidential initiatives: Climate Change Research (June 2001), Global Earth Observation (July 2003), and the Vision for Space Exploration (February 2004).

The Earth is the only harbor for highly diversified life yet found in the universe. In contrast to its neighbors Mars and Venus, Earth's atmosphere shields our planet to maintain an environment conducive to life and human civilization. What are the underlying features and processes that enable life on Earth? How are these sustained? Are they replicated in part or in whole elsewhere in the universe?

Perhaps more than any other human activity, several centuries of progress in flight have steadily changed our perception of the Earth as a home planet. Viewing the surface from aloft and now the entire planet from space, we recognize that land, seas and ice are each rich, constantly changing mosaics variously suitable for life. Adding satellite measurements of essential characteristics to stunning images from space, we have come to understand the Earth as a system of tightly coupled parts. It is now clear for example that the characteristics of Earth's atmosphere so critical to human habitability are maintained by complex and tightly coupled circulation dynamics, chemistry, and interactions with the oceans, ice and land surface; all driven by solar radiation and gravitational forces.

From the vantage point of space we also see at continental and planetary scales the vast extent and complexity of human activities. Over the past 50 years, world population has doubled; world grain supplies tripled; and total economic output grew sevenfold. From space, we see that expanding human activities now affect virtually the entire land surface and are altering world oceans and ice masses as well. Over the next 50 years, the world population is likely to grow to 11 billion, exerting ever more demands for habitable land and natural resources.

Thus, we live on a planet undergoing constant change due to natural phenomena and our own activities, and to maintain quality of life on Earth, we need continuous observations of variability and change over its entire surface analyzed to reveal the forces involved, the nature of the underlying processes and how these are coupled within the Earth system. To inform management, decisions, and policies, we need ongoing predictions derived from Earth observations to expose the responses that determine further change. Thus, NASA's mission in Earth science is to understand and protect our home planet by using our view from space to study the Earth system and improve predictions of Earth system change. The fundamental question:

> How is the Earth changing and what are the consequences for life on Earth?

expresses the strategic goal of this effort.

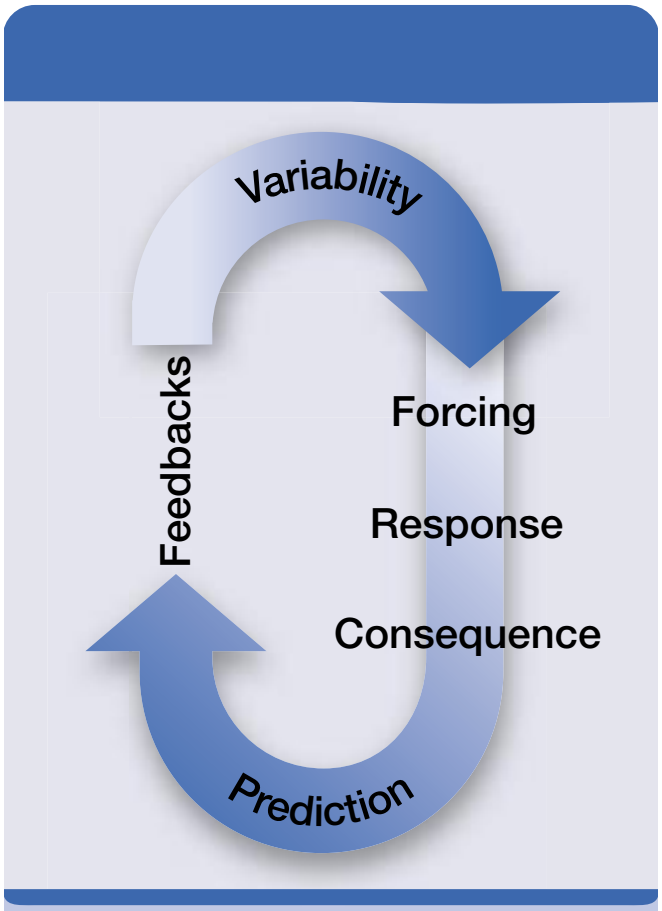
NASA's Earth observations and research focus on the Earth as a system—a dynamic set of interactions among continents, atmosphere, oceans, ice, and life. This way of studying the Earth is critical to understanding, for example, how global climate responds to the forces acting upon it. From the 1960s through the 1980s we developed the technology to view the Earth globally from space, focusing on individual components of the Earth system. This launched an era of rich scientific discovery, including the discovery of the processes behind Antarctic ozone depletion; the Earth's response to incoming solar radiation; and the extent, causes, and impacts of land use and land cover change. In the 1980s and 90s we developed the interdisciplinary field of Earth system science and began to survey the Earth system in its entirety, leading to the deployment of the first Earth Observing System. During this period, scientists used space-based observations, coupled with suborbital and in situ measurements, to uncover the mechanisms behind the El Niño-La Niña cycle and begin modeling the climate system in a meaningful way. For the first time, scientists were able to measure the global distribution of atmospheric aerosols and related changes over seasons and years. In this decade NASA is deploying new types of sensors to provide three-dimensional profiles of Earth's atmosphere and surface. In the decades beyond NASA will migrate current and new sensors to higher orbits to enable higher temporal resolution and interacting constellations of satellites.

NASA's unique capabilities in Earth system science include:

- Creating the ability to study the Earth as an integrated physical and biological system. The Agency is pioneering new remote sensing capabilities from a variety of vantage points. Global-scale changes require a global perspective; local and regional changes can only be fully understood in their global context.
- Addressing fundamental scientific questions with an end-to-end approach that integrates Earth observation, interdisciplinary research, and Earth system modeling, providing comprehensive results to Earth science questions that inform natural resource management, policy and economic decisions.
- Advancing remote sensing technology and computational modeling for scientific purposes, and facilitating the transition of mature observations and technologies to partner agencies that provide essential services using Earth science information.
- Forging domestic and international partnerships to explore the complex Earth system. NASA has the program management and system engineering expertise to help lead complex, multi-partner research endeavors as well as make unique contributions to those led by other nations and organizations.

NASA's Earth science programs are essential to the implementation of three major Presidential initiatives: Climate Change Research (June 2001), Global Earth Observation (July 2003), and the Vision for Space Exploration (February 2004). The first is the subject of the U.S. Climate Change Science Program (CCSP). The second is related, and focuses on national and international coordination of Earth observing capabilities to enhance their use in meeting important societal needs. An Earth Observation Summit in Brussels in February 2005 will adopt a ten year plan for a Global Earth Observation system of systems. The third initiative uses NASA's observing technologies and knowledge of Earth as a planet to aid in the Nation's exploration of worlds beyond.

Figure 1.1



Variability through forcing, response, consequences, and prediction form a fundamental paradigm underlying NASA Earth science research.

From the first weather satellite in 1960 to today's comprehensive Earth Observing System, NASA's view of our home planet has improved life on Earth. As NASA extends exploration of the Earth, Sun, solar system, and the universe, Earth observations and our increasing understanding of the Earth system will shape investigations elsewhere, providing the basis for searching for life elsewhere and for extending life beyond our home planet. Thus, while understanding and protecting our home planet is an essential element of NASA's mission, the Vision for Space Exploration opens opportunities to link Earth observations and research to missions across the solar system and beyond.

NASA provides accurate, objective scientific data and analyses to advance our understanding of the Earth system and to help policy makers and citizens achieve economic growth and effective, responsible stewardship of the Earth's resources. Earth science research aims to acquire deeper scientific understanding of the components of the Earth system, their interactions, and the consequences of changes in the Earth system for life. These interactions occur on a continuum of spatial and temporal scales ranging from short-term weather to long-term climate and motions of the solid Earth, and from local and regional to global. The challenge is to predict changes that will occur in the next decade to century, both naturally and in response to human activities. To do so requires a comprehensive scientific understanding of the entire Earth system, how its component parts and their interactions have evolved, how they function, and how they may be expected to further evolve on all time scales.

Following from the fundamental question above, five scientific questions drive Earth science research NASA:

- How is the global Earth system changing?
- What are the primary causes of change in the Earth system?
- How does the Earth system respond to natural and human-induced changes?
- What are the consequences of change in the Earth system for human civilization?
- How will the Earth system change in the future?

These core questions represent a paradigm of variability, forcing, response, consequences, predictions, and the processes that link these and maintain feedbacks within the Earth system (figure 1.1). This conceptual picture is deeply imbedded within NASA's research strategy to understand changes in the Earth system. While contributing toward and taking advantage of a rapidly developing system of Earth observations, a broad program of NASA research and development addresses these questions, both from an Earth system perspective and within traditional scientific disciplines.

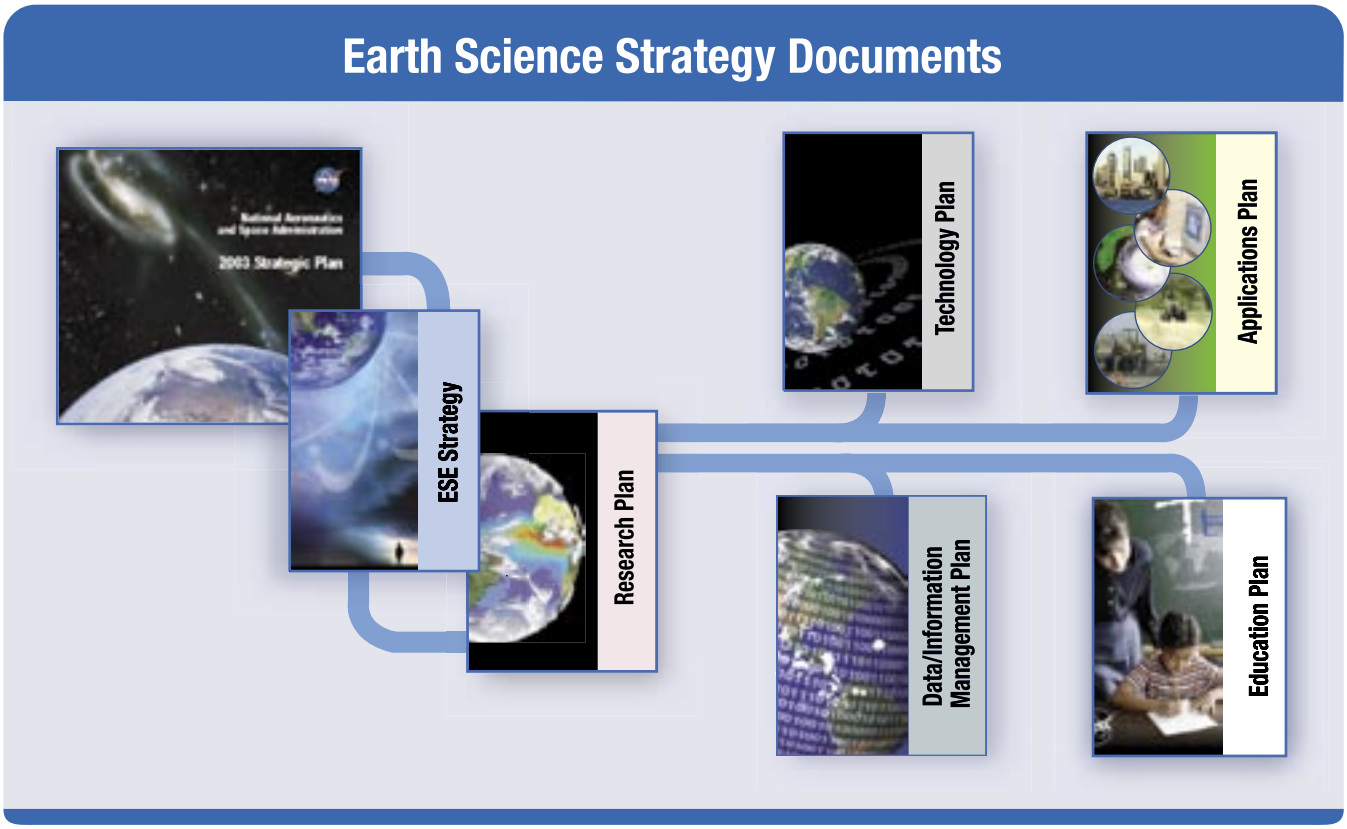
NASA recognizes that environmental variability and change have enormous societal consequences and that people are no longer passive participants in the evolution of the Earth system but instead cause significant changes in atmospheric composition, land use and land cover, water resources, and biodiversity. The fundamental principle that the Earth can only be understood as an interactive system of complex and tightly coupled components including weather and climate, water and energy cycles, global biogeochemical cycles, as well as surface and solid earth processes guides NASA in its efforts to understand and protect the planet we inhabit. This

concept of Earth system science mandates a strong interdisciplinary approach to understanding the interactions between the Earth system components.

We live in the extended atmosphere of an active star. Solar radiation drives numerous processes within the Earth system that are crucial for life and the maintenance of Earth's ecosystems. Further exploiting observations and investigations of the Sun-Earth connection is particularly important to understanding Earth's climate and biosphere. Earth and planetary science share a wealth of common understanding about fundamental processes and utilize not only similar instruments, sensors, and platforms but common models and analysis approaches as well. Interdisciplinary Earth, planetary, and space science missions can evolve an even broader view of coordinated observations in space that mesh Earth, Sun, and planetary observing systems and analyses to provide a far broader view of life on Earth and perhaps elsewhere in the universe. Subsequent editions of the Research Plan will more fully embrace the Sun-Earth connection.

This Research Plan describes the fundamental questions that underlie NASA Earth science research, the approach to addressing these through Earth observations, modeling and analysis to diagnose and predict change, the strategy for setting research priorities and for enabling work to address these, and the programs of measurements and modeling envisioned.

Figure 1.2



2 Approach to Earth System Science

Extensive observations interpreted carefully and taking advantage of rapidly improving understanding of sensors and of the character of observed variables, allow estimates of many Earth attributes and contribute critical understanding of the forces acting on the Earth, responses, and variations in the fundamental processes involved. But observational approaches alone are inadequate for addressing the fundamental Earth science questions confronting NASA. Many aspects of Earth system change happen too slowly, and many processes, such as those occurring in soils or the deep oceans, cannot be observed directly over large areas. Models provide a means of estimating forces and changes that cannot be observed directly and are a critical means of expressing our understanding of the complex subsystems of the Earth and how these interact and respond as a highly coupled system. Models link Earth observations to predictions.

The five fundamental questions described in the previous section represent a broad framework of Earth system science and a paradigm for a flexible research program focusing on Earth observations, modeling, analysis, and prediction. Table 2.1 lists specific questions that organize and direct NASA Earth science research. NASA brings unique capabilities for Earth observation from space to bear on these questions.

2.1 Research Focus Areas

NASA seeks comprehensive understanding of Earth system change, and to accomplish this, the NASA Earth science research program is necessarily broad and interdisciplinary. While NASA relies heavily on specialized expertise and resources in Earth science, its research initiatives cut across traditional scientific disciplines. To be effective in addressing the full hierarchy of questions in table 2.1, while continuing longer-term efforts to develop Earth system models and predictive capabilities, NASA Earth science research is organized within six interdisciplinary focus areas: Atmospheric Com-

Table 2.1

Hierarchy of science questions.
Overall: How is the Earth changing and what are the consequences for life on Earth?
How is the global Earth system changing? (Variability)
How are global precipitation, evaporation, and the cycling of water changing? How is the global ocean circulation varying on interannual, decadal, and longer time scales? How are global ecosystems changing? How is atmospheric composition changing? What changes are occurring in the mass of the Earth's ice cover? How is the Earth's surface being transformed by naturally occurring tectonic and climatic processes?
What are the primary forcings of the Earth system? (Forcing)
What trends in atmospheric constituents and solar radiation are driving global climate? What changes are occurring in global land cover and land use, and what are their causes? What are the motions of the Earth's interior, and how do they directly impact our environment?
How does the Earth system respond to natural and human-induced changes? (Response)
What are the effects of clouds and surface hydrologic processes on Earth's climate? How do ecosystems, land cover and biogeochemical cycles respond to and affect global environmental change? How can climate variations induce changes in the global ocean circulation? How do atmospheric trace constituents respond to and affect global environmental change? How is global sea level affected by natural variability and human-induced change in the Earth system?
What are the consequences of change in the Earth system for human civilization? (Consequences)
How are variations in local weather, precipitation and water resources related to global climate variation? What are the consequences of land cover and land use change for human societies and the sustainability of ecosystems? What are the consequences of climate change and increased human activities for coastal regions? What are the effects of global atmospheric chemical and climate changes on regional air quality?
How will the Earth system change in the future, and how can we improve predictions through advances in remote sensing observations, data assimilation and modeling? (Prediction)
How can weather forecast duration and reliability be improved? How can predictions of climate variability and change be improved? How will future changes in atmospheric composition affect ozone, climate, and global air quality? How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future? How will water cycle dynamics change in the future? How can our knowledge of earth surface change be used to predict and mitigate natural hazards?

position, Carbon Cycle and Ecosystems, Climate Variability and Change, Earth Surface and Interior, Water and Energy Cycle, and Weather.

These six focus areas include research that not only addresses the challenging hierarchy of science questions in table 2.1 but drives the development of an Earth observing capability and associated Earth system models as well. While a variety of focus areas can be proposed to organize Earth science research, specific NASA research programs fit well within the six currently adopted by the agency and align well within the major elements of U.S. and international programs.

Natural linkages underlie many fundamental Earth system processes, and multiple focus areas have interests in many of the questions and issues in table 2.1. For example, the interactions between carbon and water in photosynthesis and evapotranspiration influence large-scale exchanges between

the atmosphere and land surface so strongly that the Carbon Cycle and Ecosystems focus area and the Water and Energy Cycle focus area find common ground in many aspects of their efforts. Thus, interaction and coordination between focus areas is essential and occurs routinely as NASA solicits and coordinates Earth science research. NASA's emphasis on global observations and on Earth system science force coordinated effort across the focus areas. The Earth system modeling and analysis effort described in a subsequent section draws on scientific results, data products, and models developed within all focus areas and maintains constant integration and synthesis.

Descriptions of the six focus areas follow. Each focus area emphasizes selected questions from the list in table 2.1, but typically, research within multiple focus areas must be linked in order to address many of these questions. Roadmaps summarize the technology, observations, modeling, field campaigns, basic research, and partnerships needed over time to achieve the long-term goals for each focus area. Where focus areas collaborate closely, their roadmaps contain related items.

Each roadmap diagram portrays a strategy for a decade of progress from "where we are now" toward a goal of "where we want to be" in 2015. This strategy has at its base a foundation of systematic observations and steady improvements in understanding and modeling capabilities. Specific programmatic elements, representing major investments of resources, are layered on top of this foundation. Systematic observations are shown across the bottom of the diagram. Just continuing research utilizing these observations will extend knowledge as indicated by the upward trend; the same is true for the associated improvements immediately above the observations. Focus area programmatic elements, indicated by the horizontal arrows within the roadmap, represent new activities that

Figure 1.2

Specific Science Questions

Variability	Forcing	Response	Consequence	Prediction
Precipitation, evaporation and cycling of water changing?	Atmospheric constituents and solar radiation on climate?	Clouds and surface hydrological processes on climate?	Weather variation related to climate variation?	Weather forecasting improvement?
Global ocean circulation varying?	Changes in land cover and land use?	Ecosystems, land cover and biogeochemical cycles?	Consequences of land cover and land use change?	Improve prediction of climate variability and change?
Global ecosystems changing?	Motions of the Earth and Earth's interior?	Changes in global ocean circulation?	Coastal region impacts?	Ozone, climate and air quality impacts of atmospheric composition?
Atmospheric composition changing?		Atmospheric trace constituents responsess?	Regional air quality impacts?	Carbon cycle and ecosystem change?
Ice cover mass changing?		Sea level affected by Earth system change?		Change in water cycle dynamics?
Earth surface transformation?				Predict and mitigate natural hazards from Earth surface change?

Climate Variability and Change Roadmap

WHERE WE PLAN TO BE:

Characterization and reduction of uncertainty in long-term climate prediction; Routine probabilistic forecasts of precipitation, surface temperature, and soil moisture; Sea-level rise prediction.

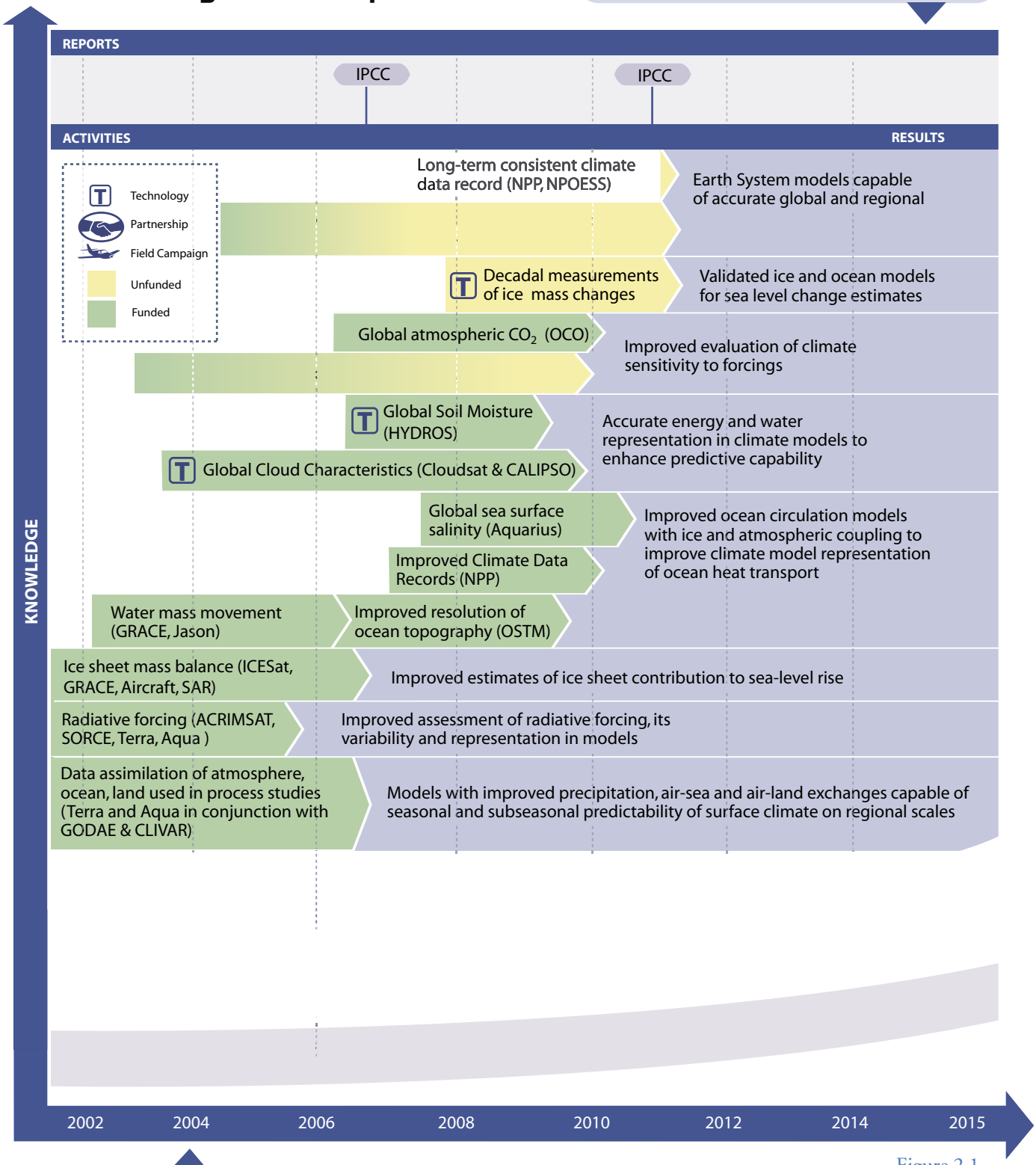


Figure 2.1

WHERE WE ARE NOW:

Experimental 12-month forecasts of surface temperature, precipitation; Fair knowledge of global climate variables and their trends; Climate models that simulate long-term global temperature change with large uncertainty in forcings and sensitivity.

will greatly increase knowledge beyond that which would be derived from just continuing the analysis of the systematic observations and through the improvements. These program elements are what enable the focus area to fully achieve its goals by 2015. The program elements are phased in time based on focus area priorities and technological readiness, as well as other programmatic criteria described in Section 4 to follow. Elements begin with conceptualization, including specification of program or mission requirements and the development of approaches. Programs end or missions launch at the point of the arrow (to the right) on the element line. Scientific outcomes follow and are described in the block to the right of the arrow.

The colors of the programmatic elements indicate their funding status, with blended colors to express partial or uncertain funding. Aircraft icons imply that an element includes an experiment or field campaign, which may or may not involve aircraft. A "T" icon means that technological development is required prior to undertaking an element. The joined hands icon signifies a significant national or international partnership in an element. Focus area research contributes to major reports and assessments; these are indicated in ovals along the top of the roadmaps. Note that multiple focus areas contribute to many of these major products.

2.1.1 Climate Variability and Change

Climate change can have tremendous consequences for the lives and livelihoods of individuals as well as for entire civilizations. While favorable climate is believed to have facilitated the "cradle of civilization" that sprang from the fertile lands of Mesopotamia, past climate change has displaced or even eliminated cultures and societies. One of the most notable displaced the Vikings, who in the late twelfth century abandoned villages and towns in Greenland and Iceland after temperatures cooled by only a few degrees centigrade.

Changes in climate can benefit or impact societies, and our ability to mitigate, adapt to, or capitalize on climatic change depends critically on understanding the processes at work and our ability to predict their future behavior. NASA's role in characterizing, understanding, and predicting climate variability and change focuses on global observations of the more slowly responding components of the system (primarily oceans and ice), naturally occurring processes and human activities that affect climate, and their interactions within the Earth system. The Climate Variability and Change Focus Area organizes NASA research to address the following major questions:

- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- What changes are occurring in the mass of the Earth's ice cover?
- How can climate variations induce changes in the global ocean circulation?
- How is global sea level affected by natural variability and human-induced change in the Earth system?
- How can predictions of climate variability and change be improved?

As depicted in the focus area roadmap (figure 2.1), climate variability and change research incorporates comprehensive observations into models that can accurately predict climatic change over seasonal, interannual, decadal, and longer time periods. NASA's research in this and the following three science focus areas is tightly coupled to the priorities of the interagency U.S. Çlimate Change Science Program.

The oceans are a major part of the climate system, and a unique NASA contribution to climate science is the near-global coverage of observations from space of selected ocean properties every 2 to 10 days. Additionally, NASA provides observations of the vast expanses of polar ice on the temporal and spatial scales necessary to detect change and sampling of the other critical elements of the climate system that link climate to other focus areas such as cloud distribution, snow cover, surface temperatures, and humidity characteristics.

The Nation benefits from NASA's substantial investments to characterize and understand the nature and variability of the climate system. Current capabilities include global measurements of sea surface topography, ocean vector winds, ice topography and motion, and mass movements of the Earth's fluid envelope and cryosphere. Critically-needed new measurements include sea-ice thickness, sea-ice snow cover, decadal change in ice-mass over land, and sea-surface salinity.

Sea ice modulates the exchange of energy, moisture, and momentum between the ocean and atmosphere and affects ocean circulation through brine rejection when formed. As such, its thickness and spatial characteristics need to be well understood. NASA investments have enabled monitoring of the spatial characteristics of sea ice, but the critical thickness dimension needs to be observed in order to sufficiently quantify the role of sea ice in the climate system and how changes in ice cover affect ocean circulation.

Atmospheric Composition Roadmap

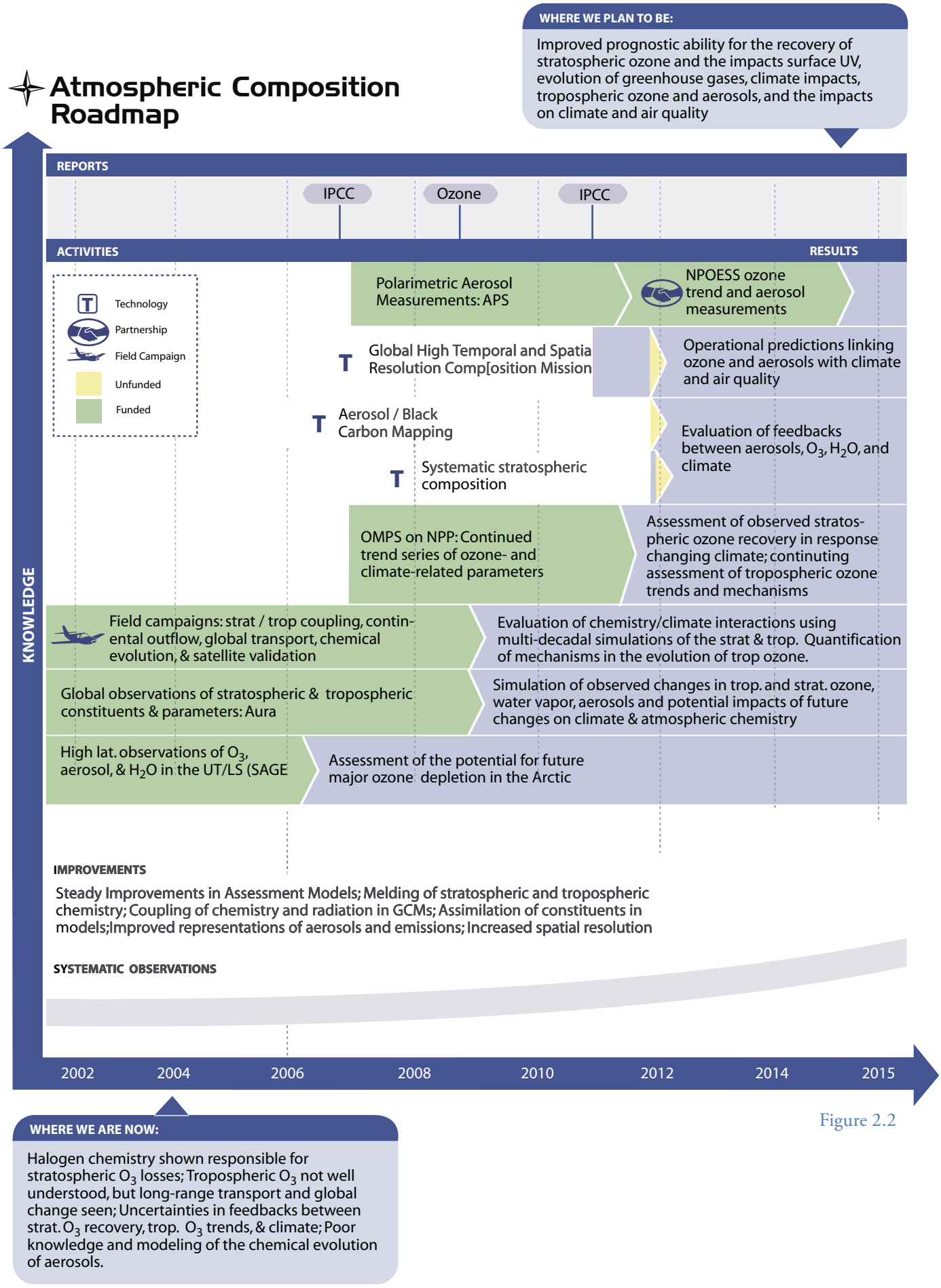


Figure 2.2

Characterizing snow depth on sea ice is also crucial to understanding the extent to which the sea-ice cover influences the broader climate. Snow is a much more effective insulator than ice, so from an energy exchange perspective, it is as important, if not more so, than sea ice. We currently have crude means of estimating snow depth on sea ice, but substantial research is needed to develop robust measurements of this parameter. Current measurements of ice mass over land must be followed by future missions to determine longer-term change in ice mass and its contribution to sea level. Ancillary measurements (e.g., ice thickness and velocity) are required to understand the mechanisms that drive these changes. Companion focus areas address complementary measurements: soil moisture, atmospheric aerosols, aerosol-cloud-radiation feedbacks, and atmospheric CO_2.

Understanding interactions within the climate system also requires strong modeling and analysis efforts. The climate system is dynamic and complex, and modeling is the only way we can effectively integrate the observations and current knowledge of individual components to fully characterize current conditions and underlying mechanisms as well as to project the future states of the climate system. This requires a concerted effort both to improve the representation of physical, chemical and biological processes in models, and to incorporate observations into climate models through data assimilation and other techniques. The ultimate objective is to enable a predictive capability of climate change on time scales ranging from seasonal to multi-decadal.

2.1.2 Atmospheric Composition

Atmospheric composition determines air quality and affects weather, climate, and critical constituents such as ozone. Exchanges with the atmosphere link terrestrial and oceanic pools within the carbon cycle and other biogeochemical cycles. Solar radiation affects atmospheric chemistry and is thus a critical factor in atmospheric composition. The ability of the atmosphere to integrate surface emissions globally on time scales from weeks to years couples several environmental issues including global ozone depletion and recovery and its impact on surface ultraviolet radiation, climate forcing by radiatively active gases and aerosols, and global air quality. Thus, atmospheric chemistry and associated composition are a central aspect of Earth system dynamics.

The research strategy for furthering our understanding of atmospheric composition is geared to providing an improved prognostic capability for the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation, the evolution of greenhouse gases and their impacts on climate, and the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality. Toward this end, research within the atmospheric composition focus area addresses the following science questions:

- How is atmospheric composition changing?
- What trends in atmospheric constituents and solar radiation are driving global climate?
- How do atmospheric trace constituents respond to and affect global environmental change?
- What are the effects of global atmospheric chemical and climate changes on regional air quality?
- How will future changes in atmospheric composition affect ozone, climate, and global air quality?

NASA expects to provide: the necessary monitoring and evaluation tools to assess the effects of climate change on ozone recovery and future atmospheric composition; improved climate forecasts based on our understanding of the forcings of global environmental change; and air quality forecasts that take into account the feedbacks between regional air quality and global climate change.

Research seeks to develop quantitative understanding of:

- Changes in atmospheric composition and the timescales over which they occur,
- Forcings (anthropogenic and natural) that drive the changes,
- Response of atmospheric trace constituents to global environmental change and the subsequent effects on global climate, and
- Effects of global atmospheric chemical and climate changes on regional air quality.

As depicted on the atmospheric composition roadmap (figure 2.2), achievements in these areas via advances in observations, data assimilation, and modeling enable improved predictive capabilities for describing how future changes in atmospheric composition affect ozone, climate, and air quality.

Drawing on global observations from space, augmented by suborbital and ground-based measurements, NASA is uniquely poised to address these issues. This integrated observational strategy is furthered via studies of atmospheric processes using unique sub-orbital platform-sensor combina-

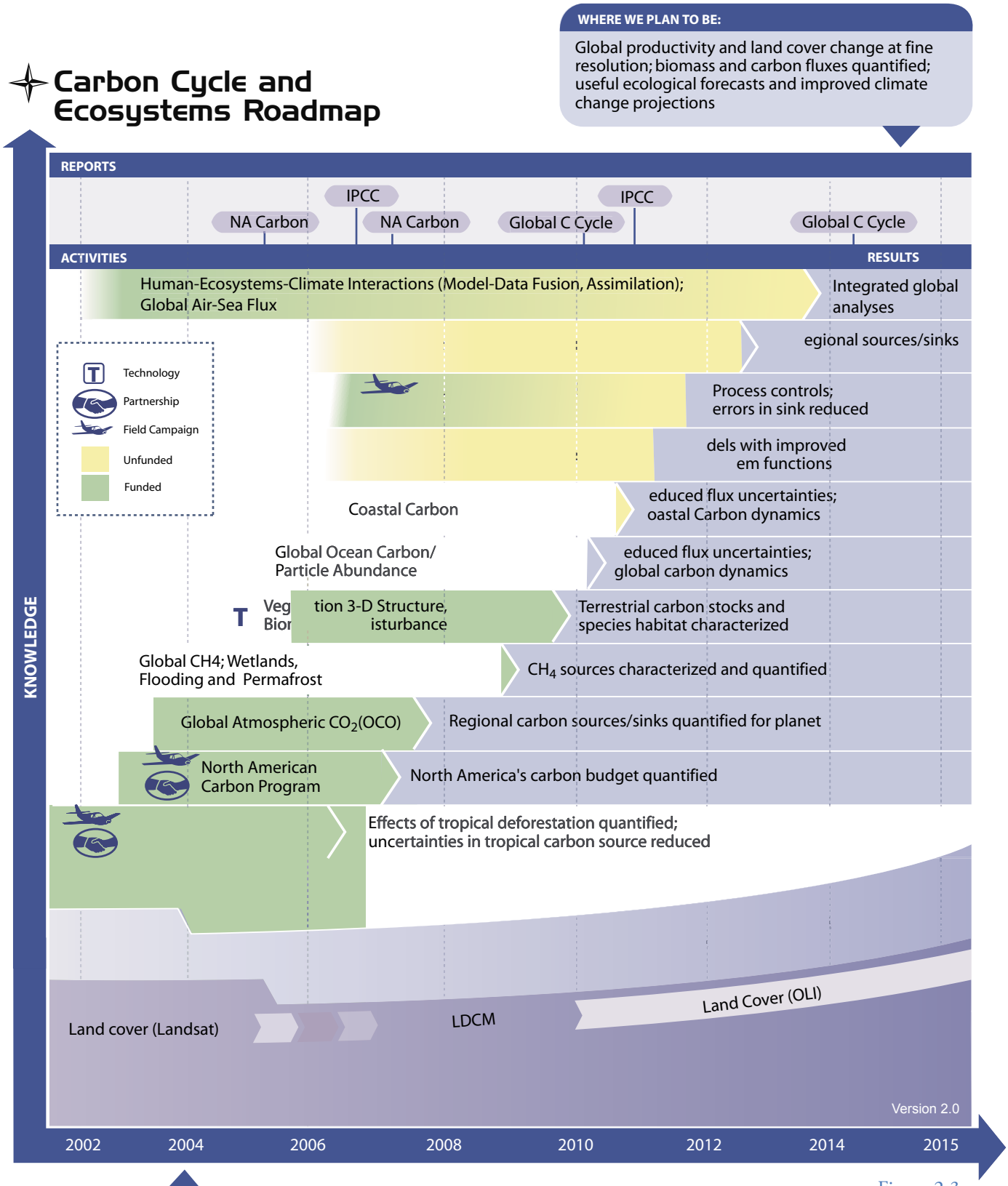

Carbon Cycle and Ecosystems Roadmap
WHERE WE PLAN TO BE:
Global productivity and land cover change at fine resolution; biomass and carbon fluxes quantified; useful ecological forecasts and improved climate change projections
REPORTS
IPCC
IPCC
NA Carbon
NA Carbon
Global C Cycle
Global C Cycle
ACTIVITIES
RESULTS
Human-Ecosystems-Climate Interactions (Model-Data Fusion, Assimilation); Global Air-Sea Flux
Integrated global analyses
egional sources/sinks
Technology
Partnership
Field Campaign
Unfunded
Funded
Process controls; errors in sink reduced
dels with improved em functions
Coastal Carbon
educed flux uncertainties; oastal Carbon dynamics
Global Ocean Carbon/ Particle Abundance
educed flux uncertainties; global carbon dynamics
T
Veg tion 3-D Structure, Bior isturbance
Terrestrial carbon stocks and species habitat characterized
Global CH4; Wetlands, Flooding and Permafrost
CH4 sources characterized and quantified
Global Atmospheric CO2(OCO)
Regional carbon sources/sinks quantified for planet
North American Carbon Program
North America's carbon budget quantified
Effects of tropical deforestation quantified; uncertainties in tropical carbon source reduced
Land cover (Landsat)
LDCM
Land Cover (OLI)
Version 2.0
KNOWLEDGE
2002
2004
2006
2008
2010
2012
2014
2015
WHERE WE ARE NOW:
2002: Global productivity and land cover resolution coarse; Large uncertainties in biomass, fluxes, disturbance, and coastal events.

Figure 2.3

tions to investigate, for example: (1) the processes responsible for the emission, uptake, transport, and chemical transformation of ozone and precursor molecules associated with its production in the troposphere and its destruction in the stratosphere; and (2) the formation, properties, and transport of aerosols in the Earth's troposphere and stratosphere. The research strategy in the atmospheric composition focus area encompasses an end-to-end approach for instrument design, data collection, analysis, interpretation, and prognostic studies.

Through the implementation of a robust program of research over the past two decades, we have made significant progress in our current level of understanding of the variability of, forcings on, responses to, and consequences of changes in atmospheric composition. However, many questions remain. For example, halogen chemistry is known to be largely responsible for stratospheric O_3 loss, but the roles of chemistry vs. dynamics remain to be precisely quantified. The connection between climate change and ozone chemistry has been recognized, but uncertainties remain regarding the effects on the timing and extent of ozone recovery. In the troposphere, we have observed varying trends in ozone; however its geographical evolution and trends remain to be quantified. Similarly, the spatial and temporal variations in the oxidizing capacity require further characterization. Global observations have shown transport of tropospheric ozone over large (hemispheric) distances. However, the extent to which regional pollution can be attributed to such long-range transport remains to be quantified. In the climate area, radiatively important changes in atmospheric water vapor have been observed, but these temporal variations are not quantitatively understood so that future changes can be predicted. Observational advances have yielded important information on the geographical and vertical distribution of atmospheric aerosols. Nevertheless significant further study is required before we can fully quantify aerosol evolution, composition, vertical distribution, and radiative impacts at a level where the information can be used in climate models.

2.1.3 Carbon Cycle and Ecosystems

Environmental change and human activities alter Earth's ecosystems and the biogeochemical cycles that are critical to the habitability of our planet. In addition to providing habitat and natural resources while nurturing crucial biodiversity, ecosystems interact with numerous geochemical and physical systems to maintain the global carbon cycle and its control over changes in atmospheric CO_2 and CH_4 and thus climate. Over the past two centuries, fossil fuel emissions and other human activities increased atmospheric CO_2 by 30% and CH_4 by 150% to concentrations unprecedented over the past 400,000 years. Discerning the response of the Earth system to these changes is fundamental to NASA's mission to understand and protect our home planet.

Ecosystems respond continuously to environmental variability and change as well as to numerous disturbances by human activities and natural events. Responses range from changes in ecosystem distribution and extent; impacts on natural resources (e.g., food, fiber, fuel, and pharmaceutical products); ecosystem services (e.g., cleaning of water and air, climate and weather regulation, carbon and nutrient storage and cycling, habitat, maintenance of water resources) to variations in fundamental processes including exchanges of energy, momentum, trace gases, and aerosols with the atmosphere that in turn influence climate.

Our ability to contend with these changes requires observations and fundamental understanding of the responses of ecosystem processes and dynamics to environmental change and to disturbance by human activities and natural events. We must assess the implications of these changes for food production, sustainable resource management, carbon management, conservation of biodiversity, and the maintenance of a healthy environment. In addressing these needs, the Carbon Cycle and Ecosystems Focus Area addresses the following science questions:

- How are global ecosystems changing?
- What changes are occurring in global land cover and land use, and what are their causes?
- How do ecosystems, land cover and biogeochemical cycles respond to and affect global environmental change?
- What are the consequences of land cover and land use change for human societies and the sustainability of ecosystems?
- What are the consequences of climate change and increased human activities for coastal regions?
- How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future?

The Carbon Cycle and Ecosystems Roadmap (figure 2.3) summarizes NASA's strategy for using the global, synoptic perspective of remote sensing to document and understand changes in Earth's carbon cycle, land cover, and ecosystems.

The focus area addresses the distribution and cycling of carbon among the active land, ocean, and atmospheric reservoirs and ecosystems as they are affected by human activity, as they

change due to their own intrinsic biogeochemical dynamics, and as they respond to climatic variations and, in turn, affect climate. The goals are to:

- Quantify global productivity, biomass, carbon fluxes, and changes in land cover;
- Document and understand how the global carbon cycle, terrestrial and marine ecosystems, and land cover and use are changing; and
- Provide useful projections of future changes in global carbon cycling and terrestrial and marine ecosystems for use in ecological forecasting and for improving climate change predictions.

Research focuses on providing data and information derived from space-based remote sensing systems to answer focus area science questions. In order to address the heterogeneity of living systems, frequent repeat observations at both moderate and high spatial resolutions are required. Complementary airborne and in situ observations, intensive field campaigns and related process studies, fundamental research, data and information systems, and modeling are all essential for interpreting satellite observations and providing answers to focus area science questions.

The ultimate goal is to project future conditions and trends for ecosystems and the global carbon cycle. This focus area contributes to the improvement of climate projections for 50–100 years into the future by providing key inputs for climate models, including future atmospheric CO_2 and CH_4 concentrations and representations of key ecosystem and carbon cycle process controls on the climate system. The outbreak and spread of harmful algal blooms, occurrence and spread of invasive exotic species, and the productivity of forest and agricultural systems exemplify ecological forecasts. Resource managers need such forecasts in order to warn the public, target the deployment of resources for mitigation or containment, plant different crops or employ alternative management practices. Policy makers need such forecasts to assess the impacts of various response options and plan for market responses and societal consequences.

Major challenges for the next decade are to document, quantify, and explain decadal-scale variability and trends in both aquatic and terrestrial primary productivity at kilometer spatial resolution, perform repeated high-resolution (~30 m) inventories of land cover and land use change, and report annual balanced global carbon budgets. To meet these challenges, we must characterize and quantify interannual variability, understand key controlling processes, and identify and quantify sources and sinks at sub-regional (~100 km) scales, both on land and within ocean margins. New insight about physiology (e.g., stress effects and efficiency of photosynthetic light use) and the ability to identify groups of species called "functional groups" with similar ecological functions (e.g., nitrogen fixing species, dimethyl-sulfide producers, invasive species) are critical to better understanding of primary productivity and carbon dynamics both on the land and in the ocean.

Well-calibrated and validated systematic observations of moderate-resolution ocean color, vegetation biophysical properties, fire, and land cover as well as high-resolution land cover comprise a critical foundation for focus area research. Major advances in knowledge require the new activities delineated on the roadmap (figure 2.3). The Large-Scale Biosphere Atmosphere Experiment in Amazonia (LBA) to understand the effects of tropical forest conversion, re-growth, and selective logging on carbon storage, nutrient dynamics, and trace gas fluxes is entering its final synthesis and integration phase. As LBA is completed, emphasis is shifting to the interagency North American Carbon Program (NACP) in order to quantify and explain North America's carbon balance. A new ESSP satellite mission to measure atmospheric CO_2 and advance our ability to quantify regional carbon sources and sinks is in the early stages of development.

New measurements of vegetation three-dimensional structure and high resolution atmospheric CO_2 profiles will be needed to quantify terrestrial carbon stocks and global sources and sinks, respectively, with sufficient accuracy to balance the global carbon budget and monitor carbon management (both sequestration and emissions reduction) activities. New information on vegetation structure also will enable the characterization of species habitats important for improved ecological forecasts. New measurements of carbon in the coastal ocean and of particle content or profiles throughout the ocean will be needed to reduce uncertainties in coastal carbon fluxes and to quantify carbon export to the deep ocean. In 5–10 years, an intensive Southern Ocean carbon program will be needed to resolve uncertainties in the size, dynamics, and global significance of the Southern Ocean as a carbon sink as well as the processes controlling this sink. In addition, new types of measurements will be needed to characterize plant physiological processes and identify plant functional groups in order to improve process characterizations in ecological models; the candidate measurement technologies (e.g., hyper-spectral, multi-spectral lidar) and analysis approaches will require study and development.

Throughout the next decade, research will be needed to advance our understanding of and ability to model human-ecosystem-climate interactions so that an integrated understanding of Earth system function can be applied to our goals. Changes in social, economic, and cultural systems are combining with global environmental changes as forcings of change in a world that is more populated, urban, and interconnected than ever before. Innovative research to blend social and natural science information and to advance model coupling, model-data fusion, and data assimilation approaches will be needed.

NASA research in the Carbon Cycle and Ecosystems Focus Area will employ the global, synoptic perspective of space and unique NASA scientific and management expertise to reduce uncertainties and provide quantitative information concerning atmospheric concentrations of greenhouse gases, changes in terrestrial ecosystem and oceanic carbon sinks, trends in primary productivity, species extinction and invasion, land cover and land use change, and the health and sustainability of global ecosystems. Continuing NASA research will focus on tracking, comprehending, and predicting these changes and their impacts on society and the Earth system. Specifically this program of research will produce:

- Assessments of ecosystem response to climatic and other environmental changes and the effects on food, fiber, biodiversity, primary productivity, and other ecological goods and services;
- Quantitative carbon budgets for key ecosystems along with the identification of sources and sinks of carbon dioxide and other greenhouse gases;
- Documentation and prediction of land cover and land use change as well as assessments of consequences to society and for resource sustainability;
- Understanding of ecosystem interactions with the atmosphere and hydrosphere leading to comprehensive modeling of the exchange of gases, aerosols, water, and energy among the components of the Earth system;
- Better representations of ecosystem processes within global climate models leading to more credible climate predictions.

The resulting information and scientific understanding will enable sound resource management strategies and policy decisions pertaining to carbon, agriculture, forestry, fisheries, and other natural resources.

2.1.4 Water and Energy Cycle

The availability of fresh water on planet Earth affects billions of people. Floods and drought can be life-threatening. The following questions guide research within the Water and Energy Cycle Focus Area:

- How are global precipitation, evaporation, and the cycling of water changing?
- What are the effects of clouds and surface hydrologic processes on Earth's climate?
- How are variations in local weather, precipitation and water resources related to global climate variation?
- How will water cycle dynamics change in the future?

As these water and energy cycle questions are addressed, we gain the understanding and observing capabilities to better contend with the hydrologic, water resource, and related weather issues that underlie habitability of the planet.

The Water and Energy Cycle Focus Area studies the distribution, transport, and transformation of water and energy within the Earth system. Since solar energy drives water and energy exchanges, the energy cycle and the water cycle are intimately entwined. Thus, research focuses on the closely linked budgets of energy and moisture. Focus area research is aligned with national and international programs including the Global Energy and Water Cycle Experiment and the water cycle activities of the U.S. Climate Change Science Program.

The overarching, long-term goal of the Water and Energy Cycle Focus Area is to develop capabilities to observe, model, and predict the water and energy cycles, including phenomena at regional scales and extreme events such as drought and floods. This goal requires an accounting of the key reservoirs and fluxes within the global water and energy cycles, including their spatial and temporal variability, through integration of all necessary observations and research tools. Further, this goal requires not only documenting and predicting trends in the rate of the Earth's water and energy cycling, but also changes in the frequency and intensity of related meteorological and hydrologic events.

The approach to these goals rests on a combination of observations, understanding, modeling, prediction, and decision-support systems presented in the Water and Energy Cycle Roadmap (figure 2.4). This integrated approach will yield improved overall knowledge and improved predictions of the changing of the water and energy cycles. Future mis-

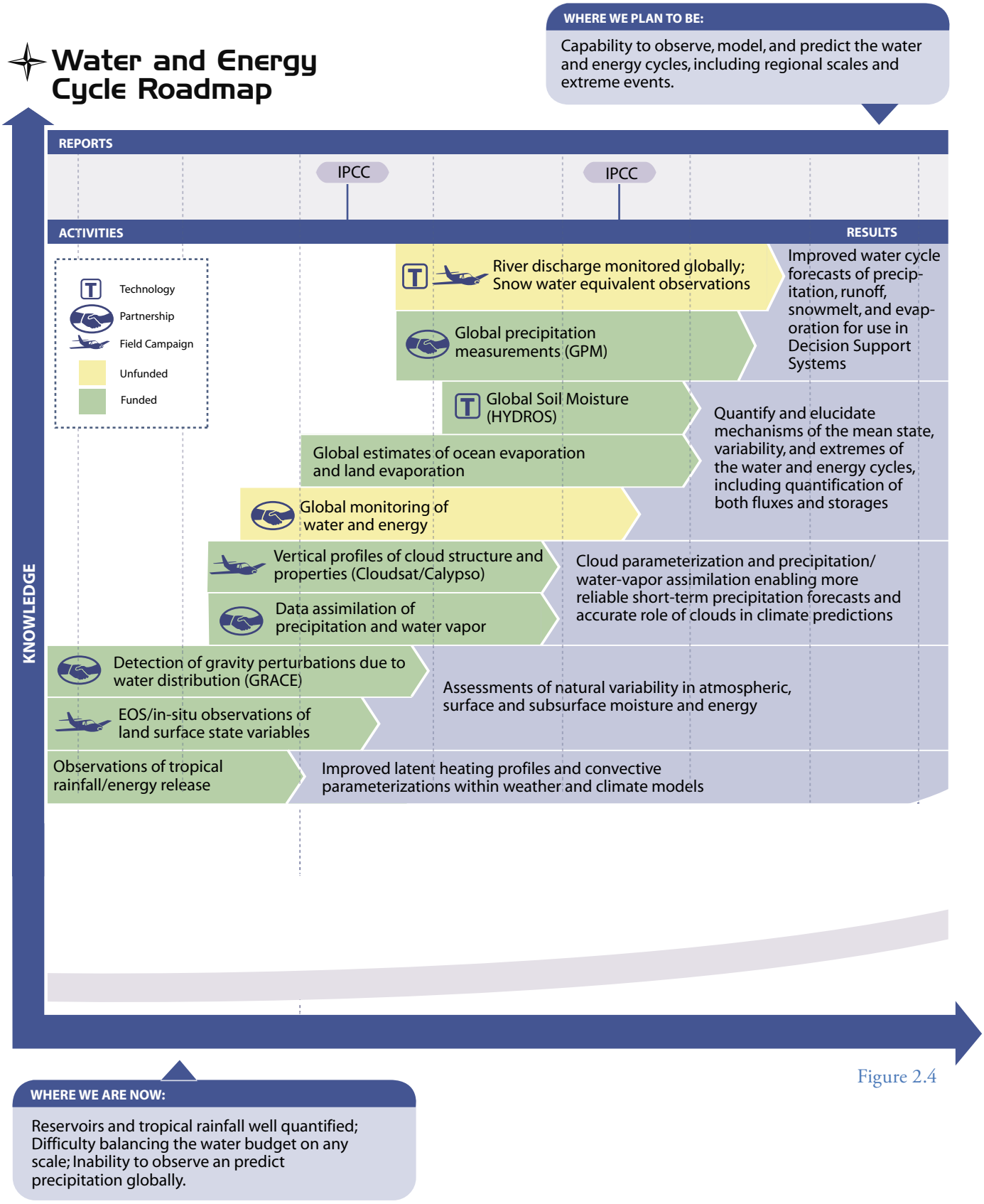

Water and Energy Cycle Roadmap
WHERE WE PLAN TO BE:
Capability to observe, model, and predict the water and energy cycles, including regional scales and extreme events.
REPORTS
IPCC
IPCC
ACTIVITIES
RESULTS
Technology
Partnership
Field Campaign
Unfunded
Funded
River discharge monitored globally; Snow water equivalent observations
Global precipitation measurements (GPM)
Improved water cycle forecasts of precipitation, runoff, snowmelt, and evaporation for use in Decision Support Systems
Global Soil Moisture (HYDROS)
Global estimates of ocean evaporation and land evaporation
Global monitoring of water and energy
Quantify and elucidate mechanisms of the mean state, variability, and extremes of the water and energy cycles, including quantification of both fluxes and storages
Vertical profiles of cloud structure and properties (Cloudsat/Calypso)
Data assimilation of precipitation and water vapor
Cloud parameterization and precipitation/ water-vapor assimilation enabling more reliable short-term precipitation forecasts and accurate role of clouds in climate predictions
Detection of gravity perturbations due to water distribution (GRACE)
EOS/in-situ observations of land surface state variables
Assessments of natural variability in atmospheric, surface and subsurface moisture and energy
Observations of tropical rainfall/energy release
Improved latent heating profiles and convective parameterizations within weather and climate models
KNOWLEDGE
WHERE WE ARE NOW:
Reservoirs and tropical rainfall well quantified; Difficulty balancing the water budget on any scale; Inability to observe an predict precipitation globally.

Figure 2.4

sions on the roadmap will provide key measurements for this focus area including: soil moisture, ocean water storage and flux, global precipitation, ground-water storage, tropospheric water storage, and atmospheric water and energy storage.

Precipitation has only recently been measured from space by the Tropical Rainfall Measuring Mission (GPM). The Global Precipitation Measurement mission will extend remote sensing of precipitation globally, allowing estimation of this input term in Earth's water budget. Evaporation cannot be measured directly, but can be estimated using models based on estimates of the amount of radiation absorbed by the land, oceans, and atmosphere and validated using selected satellite measurements including ocean salinity from Aquarius and soil moisture from HYDROS. The Water and Energy Cycle Focus Area concentrates on storage as soil moisture, ground water, surface water, and snow.

Other missions whose primary measurements address the needs of other focus areas will provide inputs on sea ice, atmospheric water content, land use and land cover, and total ocean water content. Simultaneous measurements over a two- to three-year period are critical to balancing the water and energy budgets. Measurements of soil moisture with two- to three-day frequency set the highest required temporal resolution within the budgets.

Algorithms for future sensors that can provide better spatial and temporal resolution and coverage are developed through airborne and in situ campaigns and a robust research and analysis program. In situ measurements are used to validate spaceborne measurements and model results. Future measurements, high-resolution soil moisture measurements on a global scale, surface water in rivers and lakes, and snow water equivalent will require some new technologies to be developed, in larger apertures for both passive and active microwave instruments. Higher resolution soil moisture measurements on a global scale will also require improved downlink capabilities.

Water and energy cycle modeling requires projections of future changes in surface hydrological parameters (soil moisture, runoff, evapotranspiration) due to changes in land use and land cover as well as enhancements to radiative transfer models to support finer details of atmospheric interactions.

Water and energy cycle research activities should augment and help connect the goals of the Weather Focus Area, where fast processes are studied, and the Climate Variability and Change Focus Area, where longer term process are studied. To achieve the desired accuracy in characterizing the water budget requires several key climatic inputs including sea-ice extent, as well as atmospheric water content at all levels. The energy budget requires significant inputs on solar radiation and Earth radiation.

By 2015, research within the Water and Energy Cycle Focus Area is expected to improve intermediate range forecasts for droughts and seasonal water supply and predict global scale energy storage and transport in the atmosphere by meeting two goals:

- Enable seasonal precipitation forecasts with greater than 75% accuracy at 10's of km resolution; and
- Balance global water and energy budgets.

2.1.5 Weather

Weather has enormous influence on human activities. Favorable weather is in many cases critical for agricultural productivity while severe weather can disrupt virtually every enterprise and endanger human life, property, and natural resources. Accurate weather prediction allows preparation for severe events and adaptation to day-to-day variations. Accurate hurricane predictions as well as tornado tracking save lives and property. Agriculture, transportation systems, and numerous other endeavors all rely on weather forecasts for daily decisions and resource allocation. NASA and NOAA have collaborated for decades to enable NOAA to exploit new NASA observing capabilities and research to improve NOAA's operational environmental satellites and weather forecasting models.

The direct question:

> How can weather forecast duration and reliability be improved?

guides research within NASA's Weather Focus Area.

The Weather Focus Area seeks to apply NASA remote sensing expertise to obtain accurate and globally-distributed measurements of the atmosphere for assimilation into operational weather forecast models thereby improving and extending weather predictions. As shown in the weather roadmap (figure 2.5) developed in collaboration with the U.S. Weather Research Program, a primary component of NASA's effort is directed toward resolving challenging problems such as how to use remote sensing spectral data in the presence of some cloudiness and yet still achieve temperature and moisture soundings of quality similar to that obtained by instruments lofted by weather balloons.

Weather Roadmap

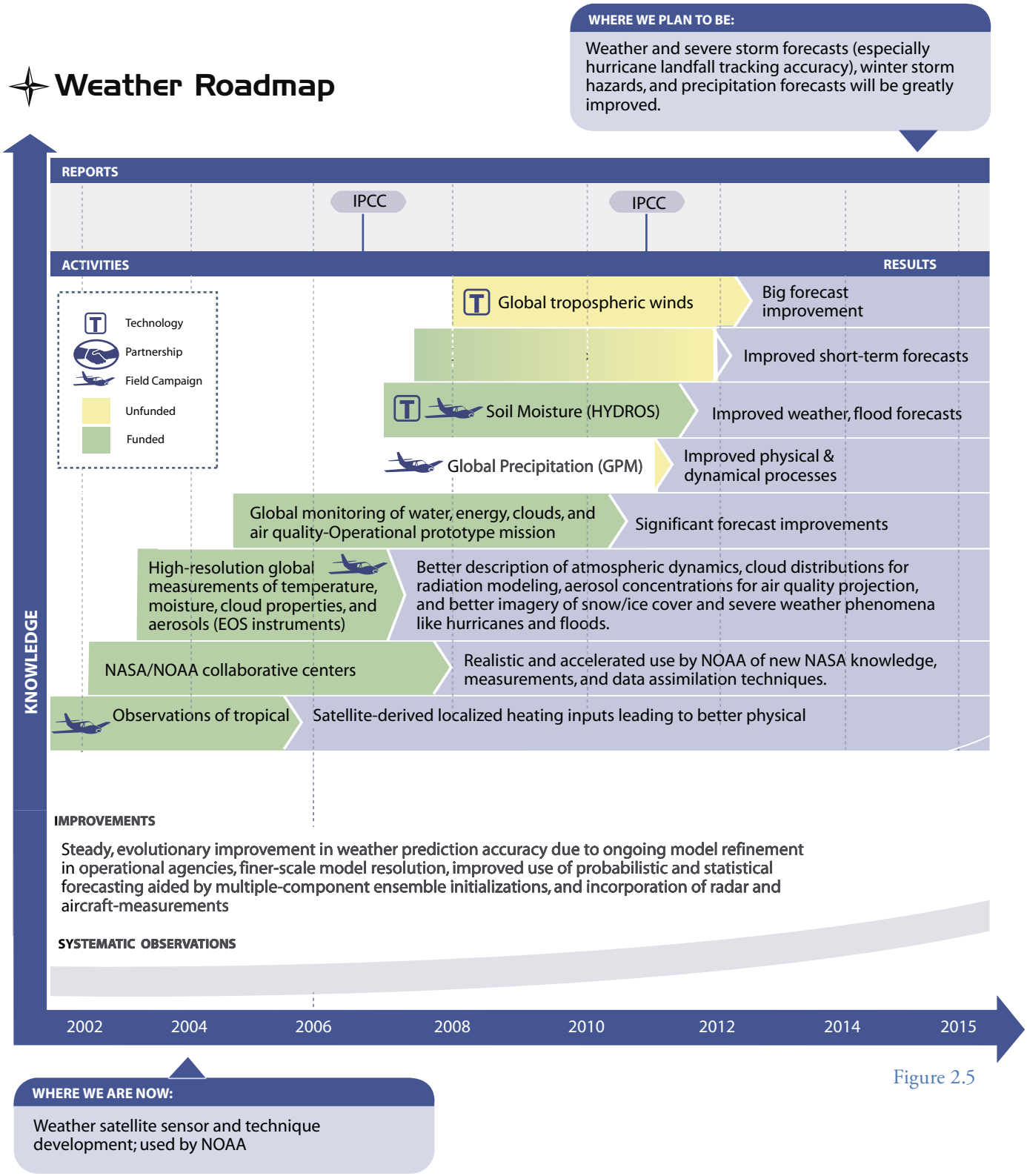


Figure 2.5

Accurate local and regional predictions begin with global simulations. These simulations require the assimilation of satellite measurements of the atmosphere in depth for the entire globe. NASA develops the satellite sensors for sounding the atmosphere's temperature and humidity structure. The latest high-accuracy sensor is the AIRS instrument on board the Aqua satellite. AIRS data are being studied intensely for inclusion into operational processing streams.

Currently, high priority is assigned to the detection and quantification of rainfall rate, generally measured by microwave remote sensing. Surface radars have long been able to estimate rainfall rate, with the assumption of appropriate drop-size distributions and a national network of Doppler radars estimate the locations of wind velocity couplets that signal likely tornado formation. NASA's first weather radar in space, TRMM, enabled global rainfall mapping throughout the seasons increased our understanding of storm-cloud characteristics accompanying various forms and levels of rainfall rates. Extension of satellite weather radar to a global constellation of active and passive sensors can pave the way for future operational missions.

Other NASA weather research is important for the design of new satellite sensors for cloud and rainfall characteristic measurement and focused field programs help researchers to understand the natural variability and structure of the atmosphere, clouds, and storms on finer and finer scales as the numerical models are able to handle the higher-resolution data.

Another key component of the current Weather Focus Area is a set of core efforts to assimilate new NASA satellite data into numerical forecast models and to assess the amount of forecast improvement. Two groups are currently working on this problem, the NASA/NOAA/USAF Joint Center for Satellite Data Assimilation and NASA's Short-term Prediction Research and Transition Center. These centers allow studies of the most effective ways of assimilating new satellite data into global and regional numerical models.

NASA's Earth Observing System provides an array of data for weather research including land and sea surface temperatures, could characteristics, bidirectional reflectance for interpreting air pollution concentrations, surface wetness, and polar winds. Not all of these measurements are currently being assimilated into numerical forecast models to determine their potential forecast impacts. As basic research concerning scales of variability and physical relationships to other parts of the Earth System is completed, additional EOS data products will be tested by NASA and NOAA for forecast improvement potential.

In addition to precipitation measurement, important new satellite missions to advance weather forecast accuracy include an operational surface moisture monitor, geostationary monitoring of lightning location, strength, and rate, and the global monitoring of vector wind fields through out the depth of the atmosphere. Perhaps the greatest value for a future satellite sensor to would be the implementation of a fleet of Doppler lidar sensors to measure global winds as a function of height.

2.1.6 Earth Surface and Interior

The Earth Surface and Interior Focus Area promotes the development and application of remote sensing to address the questions:

- How is the Earth's surface being transformed by naturally occurring tectonic and climatic processes?
- What are the motions of the Earth's interior, and how do they directly impact our environment?
- How can our knowledge of earth surface change be used to predict and mitigate natural hazards?

The overarching goal of the focus area is to assess, mitigate and forecast natural hazards that affect society, including such phenomena as earthquakes, landslides, coastal and interior erosion, floods and volcanic eruptions. The path to prediction includes comprehensively recording and understanding the variability of surface changes controlled by two types of forces: external such as climate; and the internal forces that are in turn driven by the dynamics of the Earth's interior. In order to produce a predictive capability, these observations of the Earth's transformation, must be modeled, interpreted, and understood. The advent of spaceborne sensing is vital to forecasting in the solid Earth sciences, providing a truly comprehensive perspective for monitoring the entire solid Earth system. NASA's principal partners in this focus area are the U.S. Geological Survey, the National Geospatial-Intelligence Agency (formerly NIMA), and the National Science Foundation.

Remote sensing empowers scientists to measure and understand subtle changes that reflect the response of the Earth to both the internal forces that lead to volcanic eruptions, earthquakes, landslides, and sea-level change as well as the climatic forces that sculpt the Earth's surface. A key observational

Earth Surface and Interior RoadMap

WHERE WE PLAN TO BE:

Understand plate boundary deformation & earth-quake hazards; How tectonics & climate interact ions shape the Earth's surface; Sea level changes from the interactions of ice masses, oceans, & the solid Earth

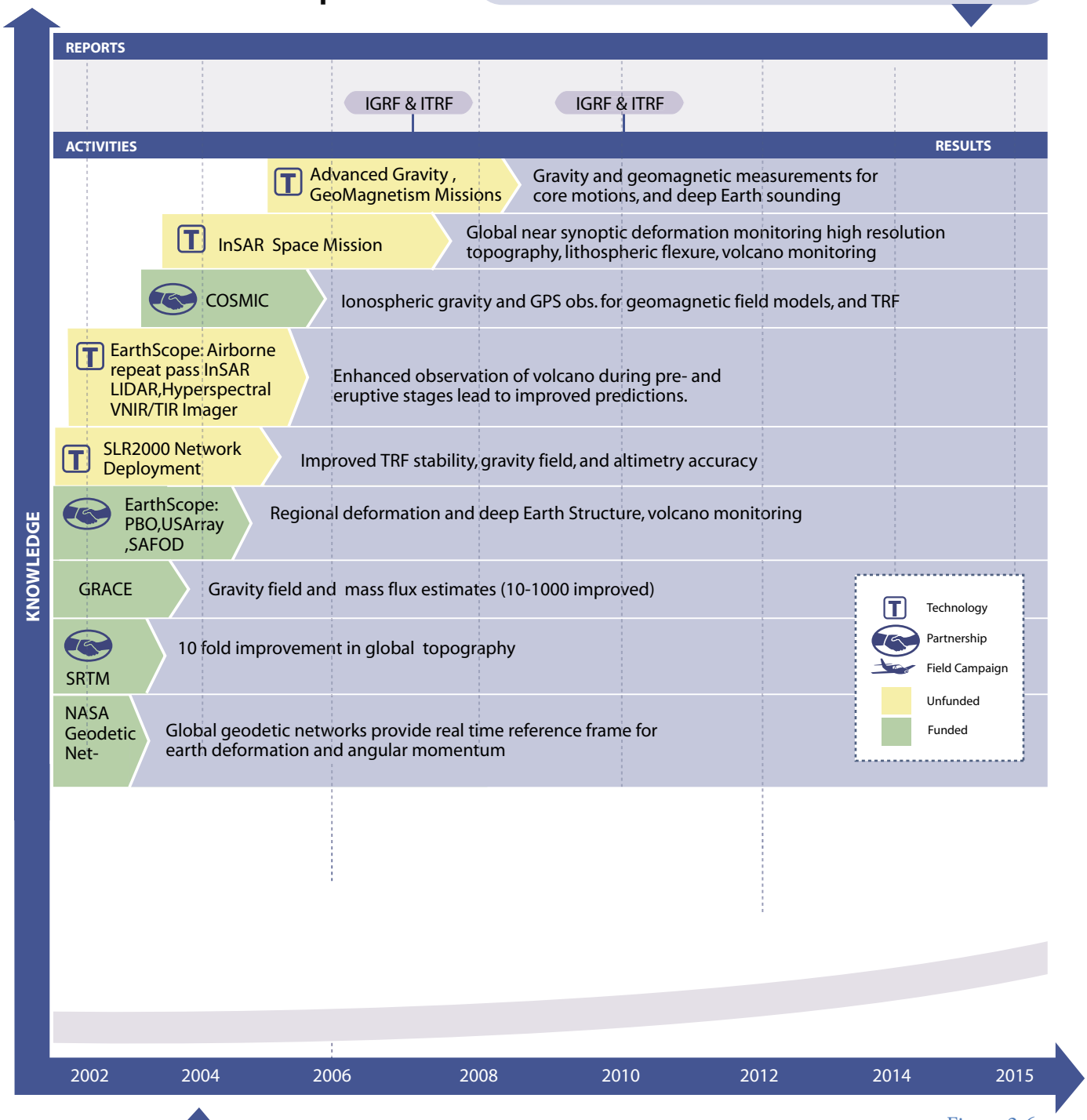


Figure 2.6

WHERE WE ARE NOW:

Space geodesy determines mm scale topography changes; Detection of Periodic and aseismic cm-scale strain events, and some seismic precur-sors. Postseismic stress changes linked to certain earthquakes; Volcanic inflation detected by InSAR reflect movement of magma at depth without seismic or eruptive signals.

strategy is to move towards geodetic and thermal imaging of the precise metrology of Earth's surface and its changes through lidar, radar constellations, and optical arrays. Such imaging coupled with geopotential field measurements will play a primary role in understanding the dynamics of the Earth's surface and interior.

The development of a stable terrestrial reference frame to better than a millimeter per year, the realization of topography and topographic change to sub-meter precision, and an understanding of changes in the Earth's angular momentum and gravity field are critical to accomplishing focus area goals. These data products provide accurate measures of changes in the Earth, including sea-level change, polar mass balance, and land subsidence. Optical and geodetic imaging using radar and lidar define the land surface to sub-meter precision to search for precursory events and to understand the Earth's surface response to both the fluid envelope and interior forces.

The Earth Surface and Interior Roadmap (figure 2.6) summarizes the elements of focus area research directed at the critical challenges of understanding the dynamics of Earth's surface and interior as a basis for predicting the occurrence of natural hazards.

The rate of sea-level change is estimated to be 1–2 mm/yr measured within the terrestrial reference frame. A critical component of these estimates is the response of the solid Earth, including subsidence and erosion in coastal zones and warping of the crust beneath the deepening oceans and thinning ice sheets. Gravity and magnetism are observables not only for the inner dynamics of the Earth but also for understanding the ionosphere, which responds to changes in the Earth's surface such as seismic waves and tsunamis, and can be used as proxies for surface motions, leading to space-based seismic imaging.

Near-term predictions of volcanic eruptions are moderately successful for certain limited and well-studied volcanic areas. These near-term predictions can be improved through better remote sensing, in particular optical and geodetic imaging coupled with enhanced computational modeling. Substantial challenges remain in modeling debris flow and long-term eruption prediction, which have a significant impact on development in volcanic regions and the global impact of mega-eruptions. Earthquake forecasting requires accurate modeling of fault interactions, which at its heart means understanding the state of stress in the crust and the strength of the lithosphere. Space geodesy is now beginning to give us a glimpse of precursory events, and the integration of geodetic and seismic models is leading to better estimates of crustal strength and dynamics in seismic zones. Visible, infrared and electromagnetic measurements are being studied for evidence of precursory phenomena and a better understanding of the physics of the earthquake cycle.

Modeling, calibration, and validation are essential components in the development of accurate forecasting capabilities. The Earth Surface and Interior Focus Area views natural laboratories as a critical component for the validation and verification of remote sensing algorithms. NASA joins with NSF and USGS in support of the EarthScope initiative to apply modern observational, analytical, and telecommunications technologies to investigate the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanic eruptions. Other natural laboratories, such as the Asian Pacific Arc and Tien Shan-Caucasus studies of convergent plate boundaries for volcanic and earthquake hazards, are under development in conjunction with international partners. The International Solid Earth Research Virtual Observatory (iSERVO) will link advanced computational resources with distributed databases developed in part from natural laboratories and NASA's remote sensing systems. The objective of iSERVO is accurate forecasting of natural hazards through the implementation of an integrated strategy of observation and computational modeling.

2.2 Observations

NASA brings unique observations from space to bear on a broad range of Earth science problems and issues, expanding our understanding of Earth system dynamics and processes while informing environmental, natural resource, and societal planning and decisions. Satellite remote sensing is the only practical means of obtaining systematic measurements over the entire Earth surface for long time periods, and many applications have come to rely on this unique resource. Satellite remote sensing is critical for extending in situ terrestrial, oceanic, and atmospheric measurements through time and over large regions. Through the continuing development of new sensors, platforms, and data products for Earth observation from space as well as the calibration, validation, and interpretation of satellite observations and their assimilation into Earth system models, NASA makes essential contributions to Earth science, observation, and monitoring.

The intellectual capital for Earth observations is vested in a robust research program. As new ideas and understanding emerge, research generates innovative observing techniques and processing algorithms, conducts field tests, and generally

charts the path for scientific and engineering developments that enable improved Earth observations. The science questions and issues that guide research within NASA's six Earth science focus areas (table 2.1) dictate broad observation requirements, and those needs with sufficient priority are incorporated into focus area roadmaps. Research addressing specific science questions sharpens requirements, in some cases identifying well-defined sensor and platform options—research projects may be focused on sensor development as a primary topic. The development of algorithms for processing remote sensing measurements into data products is a primary NASA focus in Earth science research.

To be fully successful, NASA's research in Earth observation requires close partnerships with those designing, developing, and producing remote sensing technology and satellite systems, organizations that undertake long-term monitoring by remote sensing, and national and international partners with similar interests, requirements, and missions.

2.2.1 Research and Development for Earth Observation Technology

NASA's Earth Science Technology Office (ESTO) coordinates, integrates, and manages the development of advanced technologies for use in future Earth system measurements. ESTO initiatives engage scientists and engineers from NASA centers and other government laboratories, industry, and academic institutions in technological development, risk reduction, and readiness for space missions. This effort includes not only new sensors but also the data retrieval, distribution, and processing capabilities to incorporate remote sensing measurements from space into data products for Earth science research, monitoring, and a host of applications. A companion NASA Earth Science Technology Plan (figure 1.2) describes ESTO development activities to meet the observation goals of the focus areas as expressed in their research roadmaps.

Two programs organize ESTO work on observation technologies. The Advanced Component Technologies Program implements a broad effort in technology develop for observing system components while the Instrument Incubator Program develops more mature instrument and measurement technologies that are ready for initial testing including deployment in suborbital laboratories, on balloons, or in airplanes. Similarly, the Advanced Information System Technologies program develops advanced capabilities for collecting, transmitting, processing, disseminating, and archiving information about the Earth system.

2.2.2 Satellite Missions

Since its inception, NASA has exploited satellite platforms to observe the Earth, providing a critical resource for Earth science research. As a result of growing research efforts, many measurements from space are now routine and essential. For example, satellite remote sensing has become indispensable for accurate weather forecasts and severe storm warnings. But other important measurements require new concepts that take advantage of advancing technology—many observations remain difficult to interpret. Earth science research drives NASA satellite missions, and the focus area roadmaps indicate major requirements for developing or extending satellite remote sensing.

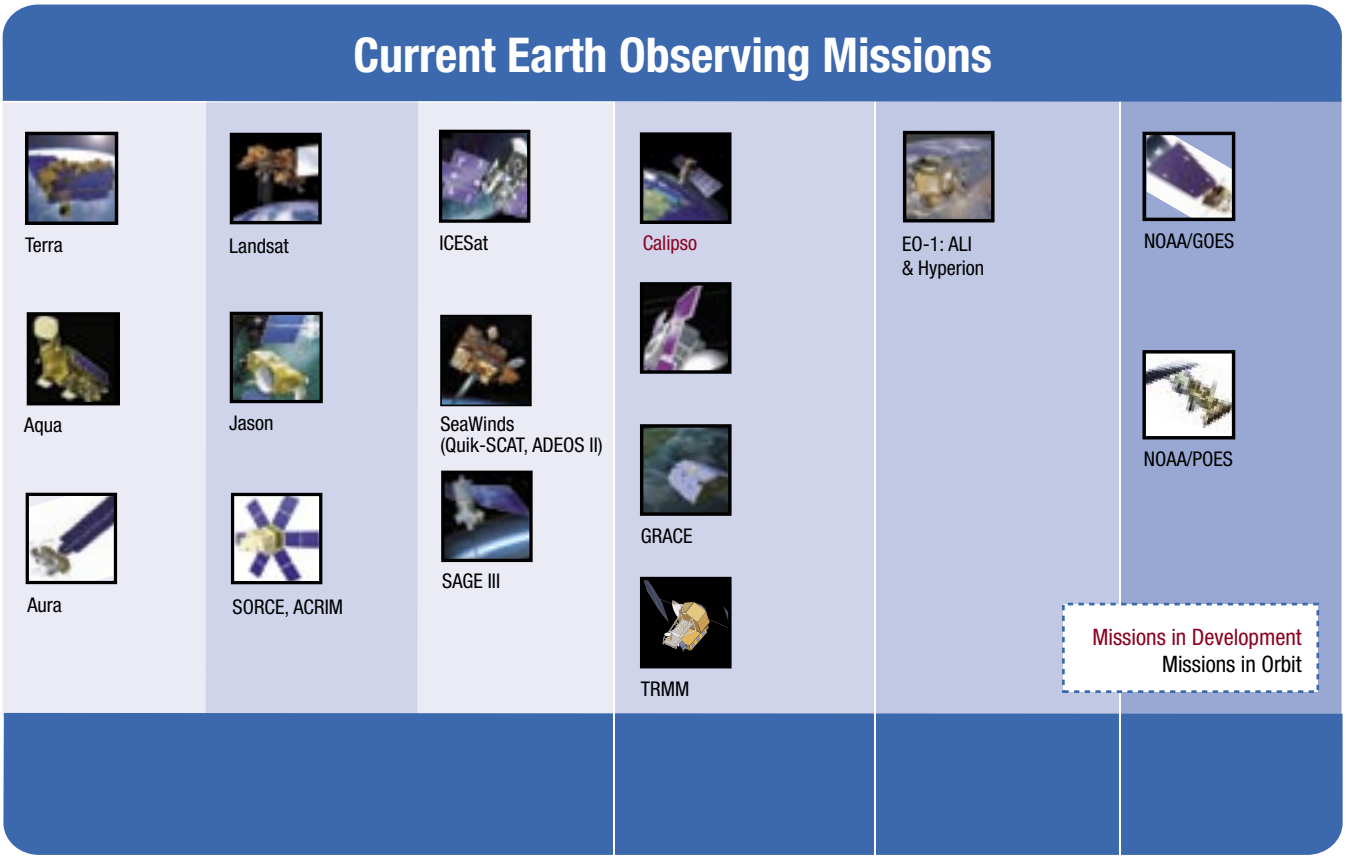
From the 1960's through the 1980's, NASA and its partners steadily advanced capabilities to observe the Earth, launching a new era of scientific discovery by remote sensing from space. Key early results include discovery of the processes behind Antarctic ozone depletion; the Earth's response to incoming solar radiation; and the extent, causes, and impacts of land use and land cover change. The emerging view of the whole Earth enabled by satellite perspectives stimulated the development of an interdisciplinary Earth system science motivated to observe a sufficient suite of characteristics and variables to identify and track change over long time periods at scales from local to global.

Beginning with the launch of the Terra satellite in December 1999, NASA began to deploy an Earth Observing System (EOS) with the objective of collecting systematic, well-calibrated and validated, long-term measurements to characterize and detect change in the Earth system (figure 2.7). A suite of polar-orbiting and low-inclination satellites, each carrying multiple sensors, linked to a data system for acquisition, processing, and distribution, provides numerous science data products with global coverage and repeated measurements of sufficient frequency and accuracy to detect change.

With the launch of Aura in July 2004, NASA completed the deployment of the first phase of the observing system that now provides a core set of data products to characterize the Earth system and to identify and track changes.

EOS data provide a foundation for Earth science research within NASA, and continuing many EOS measurements is now recognized as important not only for attaining research goals but for meeting critical decision and management needs as well. Many research activities and goals of the science focus areas hinge on EOS data products, and the focus area roadmaps show the dependence of specific research directions and goals on EOS measurements. A companion plan for Earth

Figure 2.7



Science Applications describes the use of EOS data within decision-support systems for an array of National application areas.

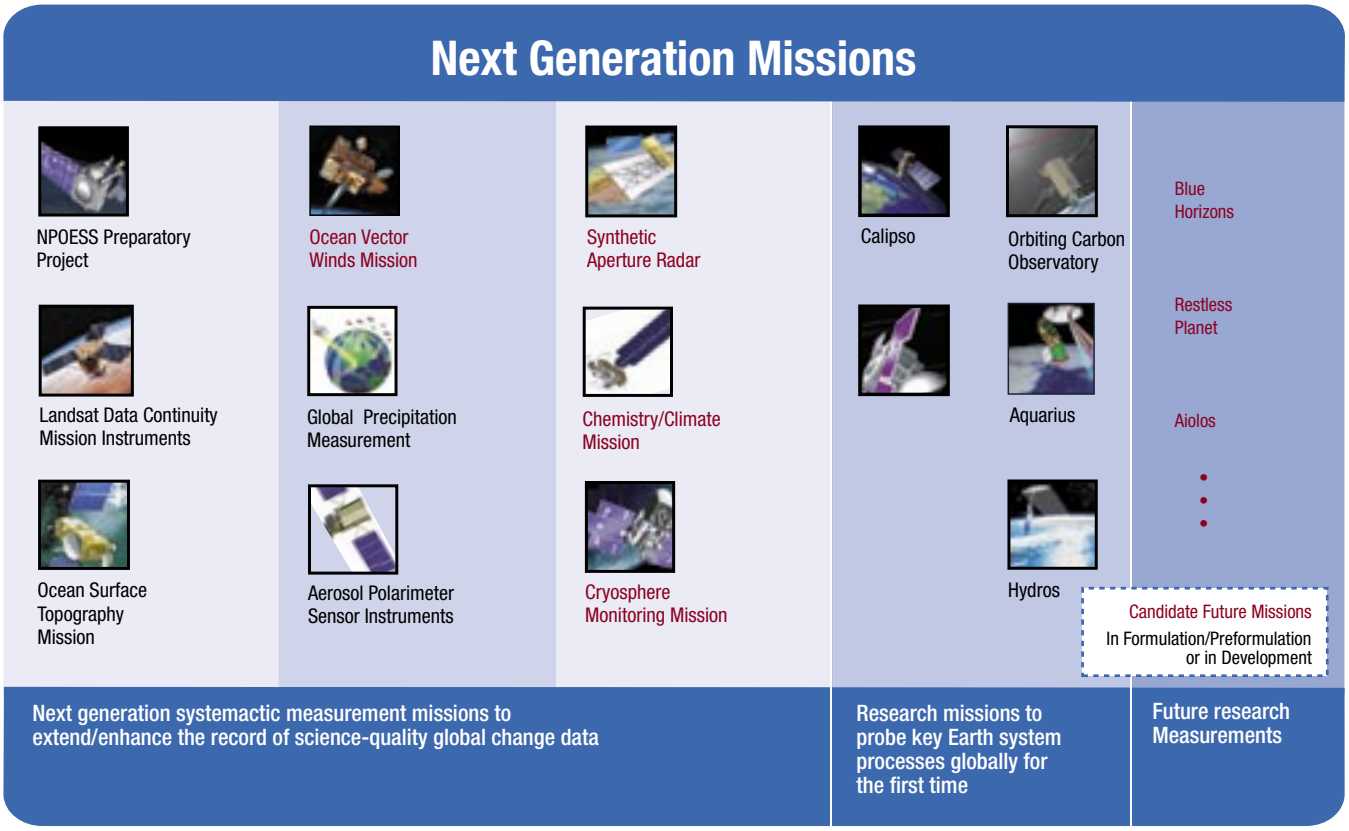
NASA, other U.S. federal and state agencies, as well as organizations in other countries support a host of research projects using EOS data. In addition to addressing scientific issues and questions, many of these efforts seek to extend Earth observing capabilities by developing improved or new data products or through new satellite missions. Research using EOS data ranges from highly-focused, single-investigator studies to large interdisciplinary programs. Investigators are making increasing use of data from multiple sensors and platforms, taking advantage of the coordinated measurements of the EOS. Formation flying by the Aqua, CALIPSO, CloudSat, Parasol, and Aura spacecraft opens new opportunities for targeted measurements in which a sensor on one platform is adjusted based on observations acquired by a sensor on a platform flying ahead in the formation.

Research is just beginning to take full advantage of the EOS. But even as unprecedented EOS data are processed and analyzed, exploratory missions continue to develop innovative observational capabilities from space that probe poorly understood processes or demonstrate new technologies (figure 2.8). The Earth System Science Pathfinder program is the primary source of exploratory missions to complement the EOS. Competitively selected Pathfinder missions address specific research questions and are developed and implemented on an aggressive schedule. Principal investigators lead Pathfinder missions from development through data distribution.

As these programs compliment and extend the Earth Observing System (figure 2.8), the domain of Earth observations from space is constantly extended.

Satellite observations are now enabling increasingly interdisciplinary Earth science research leading to better understanding of the Earth as a system that responds as a whole to forces acting on its major components. Earth system models are incorporating data from multiple sensors as constraints on model parameters and solutions. For example, measurements of atmospheric CO_2 by the Orbiting Carbon Observatory, a Pathfinder mission, coupled with observations of vegetation

Figure 2.8



phenology by the MODIS sensors provide far better understanding of seasonal variations in carbon sources and sinks on land.

2.2.3 Suborbital and Surface Observations

Measurements on land and within the Earth's atmosphere and oceans are required to calibrate and validate measurements from space and are an integral part of a complete Earth observing system. Suborbital measurements and sensors on the Earth's surface augment observations from space with higher spatial and temporal resolutions that can be targeted at specific regions or focused on specific processes. Additionally, major experiments and field campaigns provide detailed information about and understanding of systems and processes observed from space. Thus, NASA recognizes that a comprehensive Earth observing system requires a global, integrated approach combining observations from spacecraft, suborbital vehicles such as aircraft and balloons, surface instruments such as carbon flux towers and ocean buoys, as well as major experiments and field campaigns engaging multiple surface and suborbital measurements carefully coordinated with satellite observations.

Aircraft and other suborbital platforms provide laboratories for testing new approaches and sensors. Experience with suborbital observations is important for determining the value of sensors for space missions. Data collected by prototype sensors or simulators for sensors intended for satellite deployment are crucial for algorithm development and testing. In addition to their critical role in calibration, validation, and sensor development, suborbital remote sensing data compliment satellite observations with higher resolutions and less interference that are often critical for characterizing heterogeneity in space or time or for understanding complex processes.

In order to characterize Earth system dynamics and understand the processes involved, NASA undertakes selected field campaigns and experiments to collect more detailed data that can be related to satellite and suborbital observations. Such field data provide insights about system interactions and feedbacks. Understanding and quantifying these phenomena enables the development of more robust algorithms for remote sensing products beyond those closely related to the measurements collected in space.

Suborbital science within NASA is evolving from an enabling function for sensor testing and supportive observations to serve as an essential means of observing local and regional phenomena within global satellite observations.

2.2.4 Systematic Earth Observing Systems and Data Records

The U.S. Climate Change Science Program (CCSP) is developing and deploying a global, integrated, and sustained observing system to address science requirements and decision support needs at appropriate accuracies and spatial and temporal resolutions. Within this effort, CCSP seeks to address the overarching question:

> How can we provide active stewardship for an observation system that will document the evolving state of the climate system, allow for improved understanding of its changes, and contribute to improved predictive capability for society?

NASA develops critical space-based observations to meet this challenging goal and leads research to utilize Earth observations to understand the Earth system and to predict change. Currently, EOS sensors (figure 2.7) are providing unprecedented measurements of Earth system properties and variables with global coverage. The challenge for the next decade is to maintain current capabilities, implement new elements, make operational the elements that need to be sustained, and integrate observations into a comprehensive global system. The CCSP envisions an observing system that addresses research and decision support needs in climate, the global biogeochemical cycles of carbon and other elements, water, energy, atmospheric composition, and changes in land cover and land use. The goals of NASA's Earth science focus areas intentionally span the breadth of this ambitious CCSP observing system.

In the decades ahead, NASA research and Earth remote sensing missions will extend substantially our capabilities for Earth observations from space. As measurements become reliable and well understood, they will be incorporated into a growing suite of systematic observations obtained operationally. In most instances, an agency other than NASA with appropriate responsibility will undertake operational measurements and monitoring, taking advantage of and sustaining the capabilities of NASA research missions. Frequently, NASA is a partner in the development and operation of these missions.

Sustained measurements are meant to identify and monitor long-term changes in the Earth system. Such Earth system data records must meet standards that allow comparison of measurements over extended periods, frequently through the lifetimes of multiple platforms and sensors, while maintaining sufficient and well-understood accuracy. The CCSP refers to such data records as "climate quality," meaning that the records are suitable for investigating change over time periods corresponding to climatic variations and change. Achieving the necessary consistency and accuracy requires observations that conform uniformly to underlying principles. As summarized in table 2.3, the Global Climate Observing System (GCOS) specifies a core set of principles adopted by the CCSP for Earth system data records.

The GCOS principles highlight the importance of radiance calibration, calibration monitoring, and satellite-to-satellite cross-calibration. Table 2.2 summarizes additional principles for satellite systems acquiring Earth system data records.

Within NASA, the Earth science focus areas give particular attention to developing and maintaining Earth system data records. To insure integration and provide planning for the transition of research observing systems into long-term operational monitoring, focus areas designate measurement teams charged with suites of Earth system data records, and the focus area roadmaps show the transition of systematic observations into operational status. A prominent example is the incorporation of many EOS measurements into the National Polar-orbiting Operational Environmental Satellite System (NPOESS) to be operated by the Departments of Defense and Commerce in partnership with NASA.

Shorter term exploratory observations carried out with satellites, aircraft, ships, buoys, process-oriented field campaigns, and other finite duration research observations are all critical to successful deployment of satellite missions to retrieve Earth system data records. Satellite missions that bridge research systems to operational observing systems provide continuity in critical measurements, test sensor systems, and allow critical development of algorithms as well as calibration and validation schemes. The NPOESS Preparatory Project, which will continue selected EOS observations into the NPOESS era, provides the continuity not only in measurements but in algorithm development, calibration, and validation as well that is critical to obtaining Earth system data records.

2.3 Modeling, Analysis, and Prediction

A primary goal of Earth observations is to inform environmental predictions. These include climate change and its impacts; changes in atmospheric composition or in terrestrial and marine ecosystems; phenomena such as changes in ocean

Table 2.2

GCOS principles for satellite observations to acquire Earth system data records.

1. Constant sampling within the diurnal cycle, minimizing the effects of orbital decay and orbit drift, should be maintained.
2. A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations.
3. Continuity of satellite measurements through appropriate launch and orbital strategies should be ensured.
4. Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be insured.
5. On-bo
6. Operational
7. Data systems needed to facilitate user access to climate products, metadata, and raw data, including key data for delayed-mode analysis, should be established and maintained.
8. Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on de-commissioned satellites.
9. Complementar
10. Random errors and time-dependent biases in satellite observations and derived products should be identified.

circulation or El Niño events that contribute to climate variability; weather; or earthquake risk. Thus, improvements in model accuracies for predictions are an important aspect of NASA Earth science research, and prediction is a cornerstone of research within each science focus area.

Modeling and analysis are a key means of making predictions and of integrating focus area results into a comprehensive understanding of the Earth system. Modeling and analysis requirements are diverse, encompass a multiplicity of spatial and temporal scales, and involve a hierarchy of models from comprehensive, global, Earth system models to local, more process-oriented models.

The major elements of the modeling and analysis effort within NASA's Earth science research program are:

- Create data assimilation capabilities for available diverse data types;
- Develop computational modeling capabilities for research focus areas; and
- Participate in national and international scientific assessments.

During the initial Earth Observing System (EOS) implementation, NASA developed a number of critical modeling capabilities including data assimilation and tools for assessing long-term climate and global ozone change. In addition, NASA led an interagency effort to develop a framework for model coupling to enable Earth system simulation, analysis, and prediction. As EOS data became available, modeling tools saw increasing use for capturing and summarizing observations to understand Earth system processes.

The development of comprehensive models and the reconciliation of model predictions with observations is an iterative process, comprising process model development, coupling of model components, and testing to identify inconsistencies or data inadequacies. The result is a steadily improving predictive capability with regularly evaluated uncertainties. Improved models in turn clarify observational goals and metrics.

2.3.1 Exploring Interactions within the Earth System

In order to explore interactions within the Earth system, NASA:

- Links Earth system component models;
- Evaluates and constrains models through measurement comparisons and model assimilated data; and
- Characterizes key component interactions through model analysis.

Linking models is a major challenge requiring well-studied component models as well as sufficient understanding of the processes that link the components in nature, particularly boundary-layer processes that control the exchanges of momentum, energy, water, and trace chemicals. An incremental strategy will be used to link increasingly complex component models at various stages of scientific inquiry and to assure a smooth progression in state-of-the-art Earth system models within, but challenging, the limitations of computational resources.

Satellite remote sensing data coupled with expanding surface and suborbital measurements are driving models to higher spatial and temporal resolutions. But coupling models at aggressively higher resolutions is challenging. Using new observations within models is often a difficult step as well. Interactions between components occur with varying temporal and spatial scales, and nonlinearities and feedbacks can complicate scale issues. In many cases, totally new approaches to data assimilation and analysis as well as modeling are needed.

2.3.2 Distinguishing Natural from Human-Induced Change

The attribution of environmental change is a key goal in producing predictions for decision support. Differences in the spatial and temporal characteristics of natural and hu-

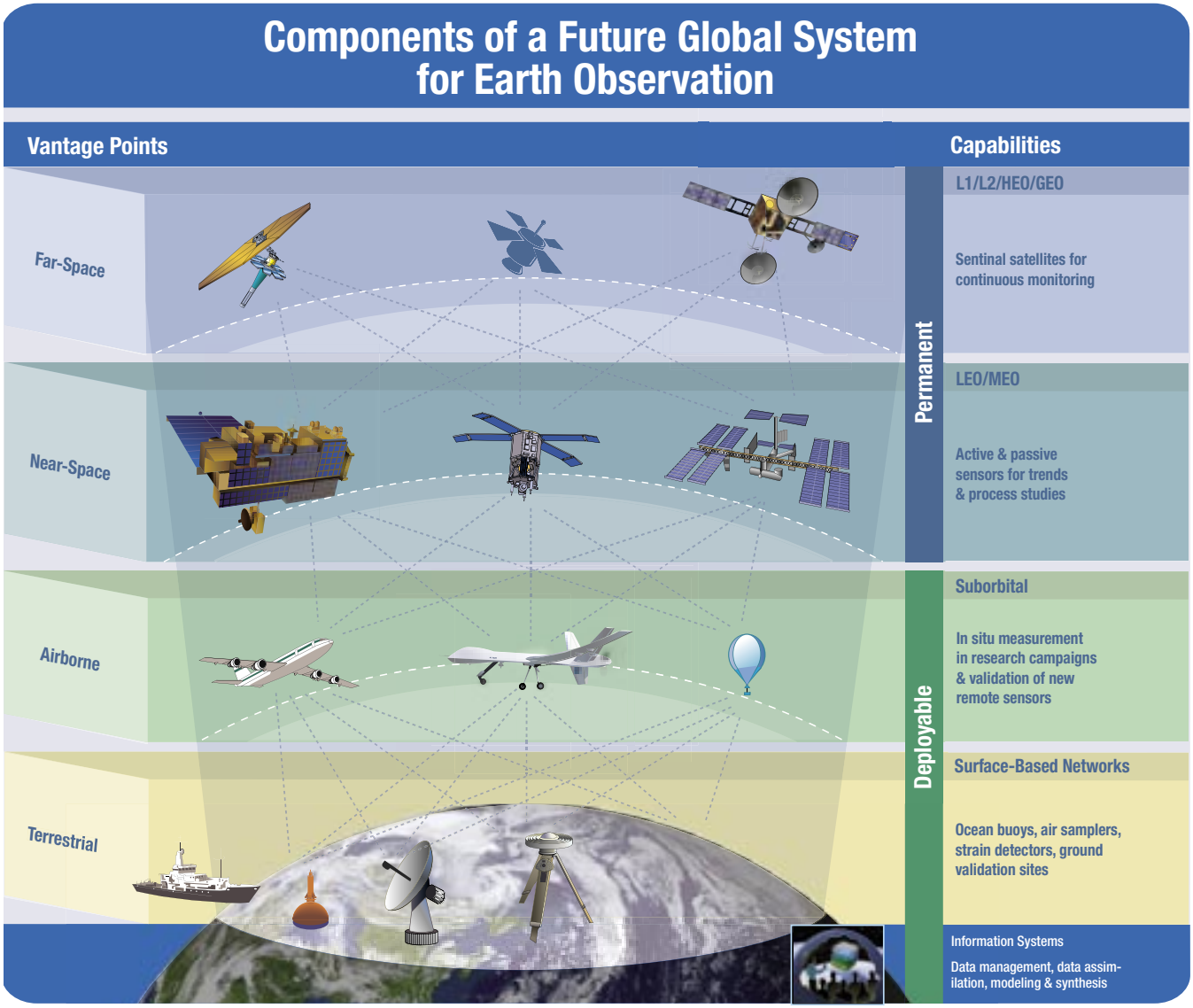
Table 2.3

GCOS climate monitoring principles.

Effective monitoring systems for climate should adhere to the following principles adopted by the Conference of the Parties to the UN Framework Convention on Climate Change through Decision 5/CP.5 of COP-5 at Bonn in November 1999:

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.
2. A suitable period of overlap for new and old observing systems is required.
3. T -
   tinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.
4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.
5. Consideration of the needs for environmental and climate-monitoring products and assessments should be integrated into national, regional, and global observing priorities.
6. Operation of historically-uninterrupted stations and observing systems should be maintained.
7. High priority for additional observations should be focused on data-poor regions, poorly-observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.
8. Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators, and instrument engineers at the outset of system design and implementation.
9. The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted.
10. Data management systems that facilitate access, use, and interpretation of data and products should be included as essential elements of climate monitoring systems.

Figure 2.9



man-induced forcings can be subtle but are resolvable given sufficiently accurate and precise measurements coupled with robust models. The NASA strategy for differentiating forcings within the Earth system includes:

- Characterize and understand model sensitivities to forcings;
- Utilize modeling tools to analyze and ascribe trends; and
- Improve estimates of environmental variability from models.

A major issue for both seasonal and long-term climate change studies is the sensitivity of models to aerosol forcing. Improved aerosol radiative parameterizations within a number of climate models are providing better understanding of the range of likely sensitivities. Anticipating a wealth of relevant global data from current and planned satellite instruments, NASA will continue to accelerate work in this area. In addition, increasing emphasis will be placed on studies of model sensitivity to solar forcing.

Historical data reanalysis using assimilation systems is very useful for diagnosis of variability in short-term climate, but

there are deficiencies in this approach. For example, momentum, heat, and moisture budgets do not balance. In regions such as tropical oceans or Arctic sea ice where important feedbacks occur, atmospheric reanalysis products are poor because they are less constrained by data and more influenced by uncertain parameterizations. Hence, the challenges for the next reanalysis products are to: (1) extract physical variability and trends from an array of artifacts including changes in the observing system or processing algorithm, (2) identify sensitivities associated with model approximations and parameterizations, and (3) increase accuracy so that they can be a tool to be used together with the satellite data for improving climate models. Concerted attacks on these issues, drawing on expertise across the science focus areas, is critical to progress.

2.3.3 Understanding and Predicting the Consequences of Earth System Change

NASA's approach to Earth system predictions includes:

- Construction of increasingly sophisticated predictive models;
- Utilization of assimilation systems to facilitate model predictions;
- Development and application of prediction accuracy metrics; and
- Conduct of model-based predictions and assessments.

Coupled Model Development.

As the interactions between various system components are characterized, NASA Earth science research will pursue fully-coupled models that include the full range of physical, chemical, and biological processes occurring within the Earth system. Such comprehensive models are conceivably needed to identify and assess the nonlinear impacts of the combined interactions and feedback processes that operate within the Earth system. Future, fully-coupled models should also be capable of simulating multiple spatial and temporal scales, given the great interest in both the scientific and policy communities for information across a wide range of scales. Such coupled models would be especially useful for regional and global assessments of future environmental trends and would help document the full diversity of expected changes in the total Earth system. Variable grid and nested models may play an important role in allowing for high spatial resolution without sacrificing computational efficiency.

The integration and coupling of various system components, however, is a daunting task unless there is coordination in development and a concerted effort to adhere to software standards. NASA supports the Earth System Modeling Framework (ESMF), which allows different modeling and assimilation groups to leverage common software tools not only for efficient development and transition to new computing architectures, but also for efficient integration and coupling. Future developments in this national collaboration will provide an environment to facilitate use of the various models under ESMF and so make models readily available to support focus area science.

Assimilation Systems

Data assimilation provides powerful constraints on predictive models by establishing reliable initializations. In assimilation, models are used to synthesize diverse in situ and satellite data streams into a single product that combines the strengths of each data set and of the model itself. The need to generate initialization fields for Numerical Weather Prediction has driven the direction of atmospheric assimilation development. Ocean assimilation products are now emerging to initialize ocean weather forecasts and seasonal predictions with coupled models as well as to improve estimates of ocean climate. Satellite altimetry makes global state estimation both feasible and meaningful. Land data assimilation is also emerging, stimulated by the availability of satellite-derived soil moisture and surface temperature.

There are many demands for data-constrained model integrations. Table 2.4 summarizes major products of model analyses that incorporate satellite and numerous surface observations. First, they are used as initial conditions for model predictions. Weather forecasts depend on the initial state of the fast components; climate projections out to a decade or more depend on the initial state of the "slow" ocean, cryosphere, and terrestrial components. Second, they are used for diagnostics of the historical climate record. Despite current limitations, assimilated fields provide the most internally consistent data sets for understanding how the climate system behaves, how natural perturbations (e.g., El Niño or the North Atlantic Oscillation) disrupt climate patterns, how extreme events are related to this variability, and how various subsystems interact. Third, assimilation analyses may serve as input to applications models of, for example, regional weather and air quality forecasting, agricultural and crop modeling, public health studies. Fourth, assimilation analyses are used as input to satellite data retrievals or to improve estimates of other satellite observed variables. Fifth, assimilation analyses can be used to infer unobserved variables. Examples of this are

vertical wind speed, which is strongly related to cloudiness properties, heating, and dynamics. and the estimate of ocean subsurface temperature and salinity structure derived from surface altimetry. Sixth, assimilation plays an essential role in defining observing system requirements through observing system experimentation.

Prediction Metrics

Prediction accuracy metrics are important measures of success in Earth science. While weather prediction has a long history of deriving and using such accuracy metrics, climate science is only beginning to explore this area. Limits on weather prediction (an initial value problem) are fairly well known, but limits on climate prediction (a boundary condition problem) remain largely unknown. Noise in weather data and in predictions increases with increasing time and space scale. Noise in climate data and predictions decrease with increasing time and space scale. These differences suggest that prediction skill metrics will vary strongly with the variable, lead time, and space scale. An important element of quantifying the prediction skill metric is identifying the controls. For example, how accurately must a model predict annual mean global, zonal, and regional cloud and radiation in order to constrain cloud feedback to reduced levels of uncertainty? The Earth science modeling program will work to improve the definition of prediction metrics, especially for the climate modeling area. For many time scales, model predictions must be verified against data in retrospective mode.

Predictions and Assessments

The atmospheric chemistry community has a long history of supporting assessments of the impacts of various disturbances on the atmospheric environment. The most widely known are the periodic Scientific Assessments of Ozone Depletion, carried out on behalf of the World Meteorological Organization and the United Nations Environment Programme as well as the assessment of climate forcing factors on behalf of the Intergovernmental Panel on Climate Change. NASA continues to support national and international assessments involving modeling and analysis with emphasis on chemical-transport models for ozone assessments, the global carbon cycle as it controls atmospheric CO_2 and CH_4, and global climate models.

Model simulations, incorporating given scenarios for changes in forcing, are the most compelling means for estimating the potential impacts of changes in the global environment. For these assessments, both retrospective, diagnostic simulations of the past evolution of the global environment, and prognostic studies to simulate potential future responses to alternative changes in forcing provide the scientific information required by responsible authorities. Seasonal prediction with coupled models provides a capstone for coupled models and assimilation systems in much the same way as weather prediction has done for atmospheric models and atmospheric assimilation.

2.4.4 Modeling Resources

As described above and in the separate science focus area discussions, NASA Earth science research requires a number of modeling approaches ranging from regional- to global-scale, data-constrained to free-running, and from single component to coupled. In moving from process to component to fully-coupled interactive models, NASA plans to significantly increase computational capability over the next decade. NASA anticipates the following priorities for computational resources:

- Model-data comparisons and data assimilation;
- Demonstration of coupled model performance; and
- Model predictions and science assessments.

Research in these areas will be selected through competitive solicitation; however, there is a continuing commitment to maintain key NASA infrastructure for data assimilation and assessment. Major drivers of computational resources will include the handling of increasingly large satellite data sets, the creation of increasingly large model codes to represent different system components, and the push toward models of higher spatial and temporal resolution in support of assessments. Specific resource decisions will be made in concert with focus area requirements and national and international assessment needs.

Table 2.4. Modeling products.

Parameter/ Question	Implementation Detail	Technical Readiness	OperationalPo-tential thru 2010	Partnership Potential
10-day weather forecasts including space shuttle mission support (P1)	10-30 km resolution global domain; extend model top to thermosphere (130 km)	30 km global ready by FY04; space shuttle support related development required	Yes	NCEP, NCAR, and ECMWF
Severe local storms (P1)	1-5 km limited area and nesting with global domain within a unified modeling system to be developed	Development of a unified regional-global modeling system required	Not cur-rently feasible; development & operational dem-onstration needed	NCEP and FSL
Hurricanes and typhoons (P1)	Minimum resolution of 55 km needed; improved initialization methodology	Track prediction ready at present; intensity prediction by 2008	Yes	National Hurricane Center; Joint Ty-phoon warning center
Local & global long-range prediction of pollutants (P3)	A comprehensive trop-strat chemistry to be implemented; high-resolu-tion sources/sinks data needed	Scientific development required; passive pollutants ready at present	Yes	Home land security dept; EPA
Winter snow storms (P1)	55 km minimum; prefer-ably at 30 km or higher	Improved land modeling & as-similation capability required	Yes	NCEP
Floods (P1, P5, P6)	Regional-global nesting required with current computing capability- high resolution topography, landcover models, rainfall, soil moisture	High-resolution (30 km or higher) global model required, High resolution topography, soil moisture, land cover data needed in addition to rainfall info	Yes	NOAA, USGS, FEMA
30-90 days forecasts (P1)	55 km or higher resolution required to be able to predict anomalies in tropi-cal storms and winter snowstorms	Coupling to ocean, dynamic sea ice, and high-resolution land model	Yes	NOAA
Droughts (P1, P5)	Impact of land usage change to be studied	Improved land modeling & assim-ilation need to be demonstrated	Yes	NOAA
Atmospheric chemistry change assessment (P3)	A comprehensive trop-strat chemistry to be implemented; bio-chemistry in land model to be developed	Scientific developments in cou-pling to atmospheric chemistry and bio-chemistry required	Yes	NOAA, DOE
Chemistry-Climate change (P2, P3)	High resolution required to access regional impacts; cou-pling to high-resolution ocean model highly desirable	High resolution pending on efficient use of the available high-end computing platform	Yes	NOAA, DOE, NSF/NCAR
Global, seasonal pre-cipitation, and surface temperature forecasts with uncertainty estimates at 12-month lead times (P2)	Ensembles of Global, coupled ocean atmosphere sea-ice models	Demonstrated capability for 6-month forecast leads; multi-model ensembles needed to compensate for different biases in different models	Very high	NOAA
Global predictions of the like-lihood of extreme weather events associated with sea-sonal climate anomalies (P2)	Large ensembles of global coupled models	Demonstrated ability of simulat-ing the observed differences in probability distributions of wintertime storms over the U.S.	High	NOAA
Global seasonal soil moisture forecasts with uncertainty estimates at 12-month lead times and at regional scales (P2, P5)	Ensembles of high resolu-tion global, coupled ocean atmosphere sea-ice models	Demonstrated capability to initialize soil moisture distribu-tions, waiting for accurate soil moisture observations	Very High	Dept of Agriculture, Forestry service

Table 2.4 Continued

Parameter/ Question	Implementation Detail	Technical Readiness	OperationalPo-tential thru 2010	Partnership Potential
Global time series of forecasts of the state of the ocean (at 1/10 degree resolution) and the atmosphere (at 1/4 degree resolution) for 1 season for diagnostics and analysis (P2)	Ensembles of Global, coupled ocean atmosphere sea-ice models	Demonstrated capability atmospheric simulations at 1/3 degree, and coupled simula-tions with the AGCM at 1 degree and ocean at 1/3 degree.	Very high	NOAA universities
Global forecasts down-scaled for regional water management and agricul-tural applications (P5)	Ensembles of high resolution global, coupled models, with statistical methods to downscale for regional hydrology models	Developments underway	Medium to high	NOAA, universities
Projections of land cover and land use change (P4)	Ensembles of high resolution, coupled natural-human system models, with methods to accom-modate regional differences	Scientific developments required in coupling models of natural system behavior with models of human system behavior	Medium to low	USDA, NSF
Ecological Forecasts for resource management and human health (e.g, invasive species; harmful algal blooms) (P4)	Advanced ecosystem models incorporating the combined effects of changes in multiple, interacting factors and human system controls	Developments underway; scientific developments in integrating human system behavior in models required	Medium	NOAA, DOI, USDA, EPA
Projections of future atmospheric concentra-tions of CO_2 and CH_4 (P3)	Global observations of atm. column CO_2 and CH_4, and biomass ingested into coupled carbon-cli-mate-human system models	Technological demonstra-tions needed; Advances in coupling natural and human system models required	Medium	NOAA, DOE, NSF, USDA,
Projections of future changes in surface hydrological parameters (soil moisture, runoff, evapotranspiration) due to changes in land use and land cover. (P5)	global inventory of land cover and land use changes on the landscape, LCLUC ingested into terrestrial hydrology models.	development is underway, advances in coupling land use with hydrology models required	Low	NOAA, USGS, NSF, USDA
Earthquake forecasting (P6)	Near realtime Global topography surface deformation and fault maps, sediment cover estimates-electromagnetic research, crustal rheology, and stress estimates, new modeling algorithms, data mining, fault interactions, TIR imaging	Poor- t InSAR and LiDAR mapping not available	Possible if proper data bases developed. Data mining predictive algorithm appears very successful.	USGS/NSF/FEMA-international collaborations
Volcano forecasting (P6)	Near realtime Global topography surface deformation and fault maps, sediment cover estimates-electromagnetic research, crustal rheology, and stress estimates, new modeling algorithms, data min-ing, fault interactions, TIR	Good; Demonstrationsuch as Pinatubo have been successful-challenge is long term forecasting	Desired	USGS/NSF/FEMA-international collaborations
Ice sheet change (P6)	Global surface deformation maps	Good; awaiting demonstration	Desired	USGS/NSF/NOAA

3 Resources

3.1 NASA Research and Space Flight Centers

NASA Research and Space Flight Centers maintain the core expertise to conceptualize, develop, deploy, and utilize systems for Earth observations from space. Center investigators serve as mission science team leaders and members, bringing critical scientific expertise with a research perspective to mission planning, operations, and data analysis. Their long-term commitments provide the intellectual continuity that is critical to successful satellite missions, spanning decades from conceptualization to final data products. Center scientists can dedicate their effort to specific observations or scientific problems and make long-term commitments to science teams prepared to undertake complex, interdisciplinary research tasks. With their focus on NASA research, centers become important repositories for the knowledge garnered from successful missions as well as for the lessons learned from less-successful efforts. This perspective is critical to both short-term and strategic research planning within the Agency.

Satellite missions and increasingly many other aspects of Earth science research rely on complicated technology developed within NASA centers and associated institutions, and NASA looks to its research programs to drive the development of critical technological resources. Day-to-day contact at NASA centers between research scientists and engineers facilitates creativity and innovation in technology while helping to insure research requirements are met. Similarly, constant exposure to technological developments provides center scientists strong understanding of emerging options, frequently fueling new ideas and research directions.

3.2 Extramural Investigators

A broad community of investigators working in universities, government laboratories, and other research institutions

throughout the world bring to NASA's Earth science research the diverse talent, training, and experience demanded by the Agency's interdisciplinary Earth system science approach. University investigators undertake approximately half of NASA's research tasks in Earth science, ranging from highly focused studies by graduate students with principle investigator guidance to satellite missions led by university investigators. At a number of institutions, teams of investigators work together with support from multiple grants or cooperative agreements, forming critical cross-disciplinary expertise. These teams may focus on specific themes or questions for extended periods, developing centers of excellence within their institutions. University investigators and scientists working at government laboratories have important roles in working groups and committees that help set research priorities and guide programs.

NASA centers maintain close partnerships with a number of universities. In some instances, university faculty work for extended periods at NASA centers, taking advantage of unique center facilities and expertise while providing their personal research perspectives. Such partnerships offer excellent opportunities for student participation in NASA Earth science research.

3.3 High-Performance Computing

Effective use of Earth observations challenges the capabilities of the world's high-performance computing systems. Our ability to predict changes in the Earth's environment depends critically on simulating biogeochemical cycles, climate, weather, and natural hazards. Such Earth system simulations, based on accurate representation of a diverse set of interacting physical, chemical, and biological processes over time scales from days to centuries, constitutes one of, if not the, most demanding computational challenges facing scientists today.

The computational demands of Earth observing systems extend from the acquisition of data from platforms in space to comprehensive Earth system simulations. The volume of remote sensing data products makes their routine production, storage, and distribution major computational requirements with unprecedented network and storage demands. Global climate and atmospheric chemistry simulations illustrate the computational demands of Earth system analyses. When satellite observations are assimilated into these simulations, the combined computational demands of data handling and model solution constitute a grand challenge in computing.

With unique capabilities in both Earth science research and the development of advanced technology, NASA is poised for a leading role in addressing these challenges. NASA is deploying advanced research computing systems at several levels as well as research and development to derive, test, and implement the algorithms and other software systems required to make effective use of the emerging hardware architectures best suited to each research task.

Through partnerships between NASA and industry, Project Columbia seeks to extend significantly the nation's high-performance computing capabilities. Capitalizing on proven technology to enhance capabilities not targeted by other leading systems, Project Columbia will develop National assets available to multiple U.S. agencies through a competitive selection process. The project will make computational resources, including networking between NASA centers, available to NASA investigators as they are developed.

Most recently, NASA acquired a cluster of 20 coupled 512 processor systems for a total of 10,240 processors. As part of Project Columbia, this high-performance system located at the NASA Ames Research Center will on completion increase NASA's high-performance computing capacity approximately 10 fold.

NASA is also investigating alternative computing architectures. Recognizing that there is no "one size fits all," the Agency is taking an overall look at what are the most reasonable architectures to satisfy computational requirements. For example, climate modeling and geodynamic modeling may require tightly coupled computing systems while earthquake modeling can tolerate loosely coupled clusters. In the future, multi-tiered computing center architecture will be built to satisfy different Earth science modeling requirements. The data system will be separated from the computing engines. A high-speed network will connect the computers with the data system and a data management system will keep track of all the data generated by the models. A wide area network connecting multiple NASA centers and universities will be used to transfer large volume of data between research groups distributed around the country.

New technologies such as Field Programmable Gate Array (FPGA) and Processor in Memory (PIM) have shown tremendous promise in on-board data procession and may be suitable for certain type of data assimilation and Earth system modeling. These will be closely watched and partnership with other agencies will be developed to exploit these alternative architectures.

Recognizing that advances in the science of Earth system modeling will require contributions from many scientists, it

is imperative that the models used be part of a Earth System Modeling Framework (ESMF) that allows for use of different model components interlinked in ways that allow for easy substitution and consistent use of data, while still maintaining high throughput and taking full advantage of the capability of the computers used. The development of this framework, which involves participants from most of the major modeling centers in the US, will enable the more rapid implementation of new algorithms into the research and assessment codes used for Earth Science modeling.

3.4 Data and Information Systems

With its focus on observations, NASA Earth science research depends on advanced data systems to acquire measurements, produce data products, provide active archives, and distribute data to research investigators. The Earth Science Data and Information Project provides scientific users, as well as a large and diverse general user community, with access to NASA's Earth science data, primarily through the Earth Observing System Data and Information System (EOSDIS). EOSDIS commands and controls NASA Earth Observing System satellites and manages data from satellites and field measurement programs, providing active archive, distribution, and information management.

Currently, NASA Earth observing satellites provide about 500 Gbytes/day (500×10^9 bytes/day) of instrument data from space, producing approximately 4 Tbytes/day (4×10^{12} bytes/day) of data products. Each year, NASA's space assets contribute about 1.4 Pbytes (1.4×10^{15} bytes/day) of data to Earth science research. This enormous data stream is the primary resource for and focus of Earth science research with NASA and fuels a broad range of research, application, management, and decision activities worldwide. As investigators better understand Earth observations from space, they improve data products and develop new ones, thus increasing data resources and at the same time data system requirements.

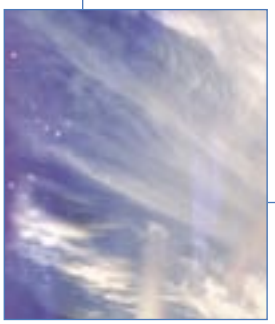
Currently managing more than 1,450 data sets and distributing data to more than 100,000 users, EOSDIS continues to serve as the primary active archive and distribution system for Earth observations obtained by NASA. Eight Distributed Active Archive Centers (DAACs), representing a wide range of Earth science disciplines, process, archive, and distribute NASA Earth observation data. Additional, tailored information products are generated and distributed by competitively-selected members of the Research, Education, and Applications Solutions Network (REASoN).

Many science data products are produced on Science Investigator-led Processing Systems under the direct control of instrument teams while others use the science data processing systems within the DAACs. In either case, the algorithms and quality assurance are provided by instrument teams.

NASA is committed to evolving its data systems to facilitate information synthesis and timely and affordable access to information and the knowledge it generates. The strategy for the next decade is to evolve data systems consistent with the science focus areas described in chapter 2 of this plan with integration across focus areas through predictive models. The major elements of the Enterprise strategy for data management are:

- Identify and generate validated climate data records in collaboration with the science community and our domestic and international partners.
- Create data assimilation capabilities sufficient to exploit the diverse data types (e.g., new satellite, sub-orbital, and in situ observations) available to create the data records needed to address Enterprise science questions.
- Participate in the development of computational, networking, and data storage/access resources to link models and assimilate observational data from diverse and distributed institutions into coupled and comprehensive Earth system models.
- Link research investigators, computational technologies, and industry to assure that evolutionary and revolutionary capabilities become available to meet rapidly-growing future performance requirements
- Lead the development of on-board computing capabilities (i.e., reconfigurable computing) to enable web sensor reconfiguration and optimization of communications bandwidth.

These will be further articulated in a new Data and Information Management Plan currently under development with NASA's external science advisory committee.



4 Implementation

4.1 Criteria for Evaluating Priorities

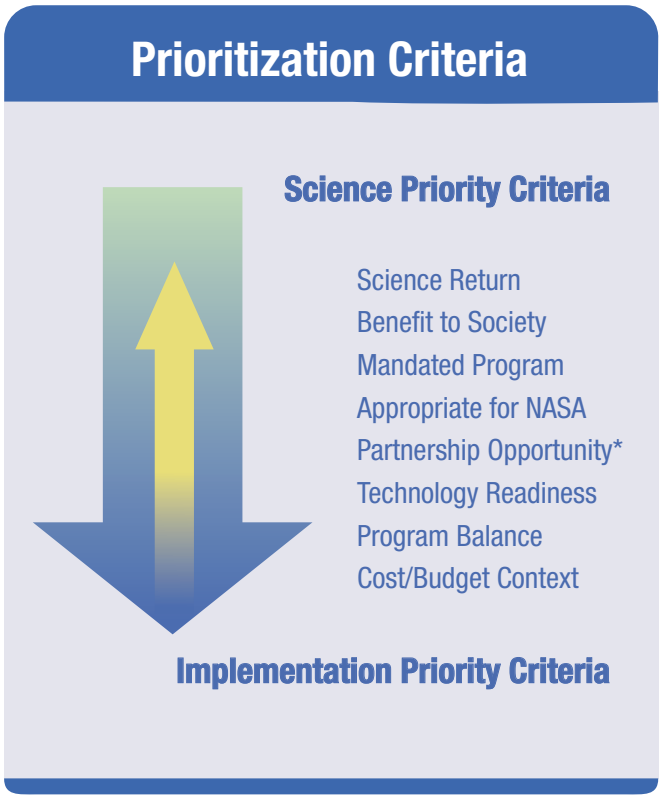
Society confronts Earth system science issues that are remarkable for their diversity of topics, complexity of interactions, and ranges of spatial and temporal scales—a vast array of initiatives offers potential contributions. NASA seeks to select research with the highest potential to improve our understanding of the Earth system while addressing critical societal questions. Optimum return from NASA's investments in Earth observations and research, measured in terms of objective information and scientific answers with societal relevance, is obtained when scientific value leads in setting priorities.

Establishing research priorities across disciplines each embracing a large set of scientific questions is a major challenge. NASA balances competing demands in the face of available resources and technology to chart a program that addresses the most important and tractable scientific questions making optimal use of NASA's unique capabilities for global observation, modeling, analysis, and basic research. Thus, NASA's research priorities reflect both scientific requirements and implementation realities. Scientific considerations are paramount and drive the prioritization process by defining science questions and ultimately by determining potential projects. But context and implementation issues can alter priority to address benefits to society, mandates, or relevance to NASA's roles. Technological feasibility shapes the order in which projects are pursued and the final shape they may take. These practical considerations often result in feedback and iteration of project selection.

Figure 4.1 summarizes criteria for setting research priorities within the NASA Earth science research. The criteria are not ordered by importance in all cases; rather, they are presented in order of procession as project concepts are conceived and matured. Application of these criteria may vary with specific

circumstances, especially given the nature of the question being investigated and the mission potentially being or project being considered.

Figure 4.1



4.1.1 Scientific Return

Scientific return is judged by the perceived significance of the problem being addressed in the overall scheme of Earth system science and anticipated technological advances toward providing definitive results. Scientific return is often high for innovative investigations that break into unexplored scientific territory. In other instances, major scientific advances are achieved only through systematic analyses of vast bodies of observations, as is often the case in the study of complex systems like the Earth. Experience demonstrates that maximum scientific return is obtained when research and observing program initiatives are conceived and designed to address specific science issues or questions. Finally, scientific priority also depends on the logical progression in approaching a complex scientific problem. Identifying the significant elements of variability in the Earth system and trends in forcing factors provides a necessary foundation for deeper insight into response mechanisms. Likewise, investigation of the consequences and the development of robust prediction methods requires a priori knowledge of the operative processes. The NASA Earth science research program represents an appropriate balance between the different steps of this progression. The potential for amplification of the Earth's response to forcing variations is an element of this choice (e.g., the positive feedback associated with changes in the distribution of atmospheric water vapor).

4.1.2 Benefit to Society

The degree to which initiatives address scientific questions of importance to society is an important measure of their benefit. Thus, the NASA structures its research plan and project priorities for Earth science around a hierarchy science questions with strong societal relevance. But observations and data products can have direct value as well and this affects the priority for underlying research. For example, better measurements may improve weather or natural hazard predictions to society's benefit short of contributing significant new understanding of the processes involved. An element of choice in selecting research programs is the potential for continuing infusion of relevant data for applications purposes. Typically, however, improved measurements and understanding go hand-in-hand.

4.1.3 Mandated Programs

Congressional direction imposes research priorities recognized as benefiting society. Specific budget guidance through the appropriations process can set research priorities. For example, recently Congress directed NASA to increase research on the global carbon cycle and atmospheric CO_2 increases. As specified by NASA's Authorization Act and by the Clean Air Act, the agency is required to maintain a research, monitoring, and technology development program for atmospheric ozone surveillance and associated atmospheric chemistry. NASA is also required to report to Congress and the Environmental Protection Agency every third year on the status of knowledge of atmospheric ozone and the abundance of ozone-depleting substances in the atmosphere.

4.1.4 Appropriate for NASA

NASA shares with other CCSP partners an interest in fundamental studies of the basic processes that govern the Earth system, diagnostic studies of recent and past data records, and model simulations/predictions of global changes. At the same time, effective use of resources requires that the NASA's Earth science strategy be focused on research projects that allow optimal use of NASA's unique capabilities. Compared to the range of investigations embraced by the entire CCSP, NASA's Earth science program emphasizes measuring changes

in forcing parameters, and documenting the natural variability of the Earth system and responses to forcings, especially through space-based measurements that can provide global coverage, high spatial resolution, and/or temporal resolution, in combinations which cannot be achieved by conventional observational networks.

Choosing among all potentially important research questions is a judgment of scientific value. In the context of NASA's Earth science research program, the principal scientific priority criteria are the spatial scale, temporal duration, and magnitude of the phenomena being investigated, as well as anticipated return in term of reducing the uncertainty in our knowledge of potential changes in the Earth system.

Research questions that address Earth system dynamics at large regional to global scales are those of greatest interest for NASA. Questions that involve smaller scale changes that have the potential to be of global significance if aggregated over a sufficiently large number of areas, are also relevant. Similarly time scales that range from seasonal, through decadal to long-term are of primary interest to NASA. This is particularly true for regions where only limited conventional (non-space) observations are available (e. g. the atmosphere over the open ocean and polar regions; continental ice sheets). For example, NASA research in atmospheric chemistry has been focused on global scale chemical processes rather than local air quality (which is typically the responsibility of regulatory environmental agencies).

Likewise preference is given to the study of phenomena and processes that may induce lasting changes in the Earth system, typically seasonal and longer period responses, as well as changes that are irreversible in the foreseeable future. Understanding and predicting fast processes (e. g. the development of weather systems, trace gas emissions) may be essential in order to quantify longer-term average impacts. While forecasting individual environmental events is not a primary NASA objective, further developing the technology for experimental prediction of specific events (e.g., weather disturbances) that can be verified by observation is a fundamental research tool for understanding changes in climate and the global environment (e. g. mean displacement in storm tracks). At the process level, priority is given to those processes that have the potential to induce large time/space scale impacts and/or are the root of large uncertainty in the overall response of the Earth system.

NASA has a very strong commitment to the use of its observational data in scientific research, and invests in the development of models and global data assimilation systems that can be used for the analysis and interpretation of observations from NASA programs and other relevant observing networks, as well as for the development of improved forecasting capability related to answering the questions posed in this plan. NASA's earth science research program also has a robust sub-orbital component, which is focused on improving our understanding of processes needed to understand, interpret, and model remotely sensed observations, as well as to contribute to the calibration and validation of the space-based observations. Innovative combinations of observing instruments and platforms are used in this component of the program.

4.1.5 Partnership Opportunity

NASA conducts Earth science research within a larger national and international context. This implies both opportunities for task sharing with partner agencies and the responsibility to seek optimal coordination of mutually supportive programs of these national and international partners. In particular, NASA has been actively seeking the cooperation of operational agencies in the US (through the National Polar-Orbiting Operational Environmental Satellite System, NPOESS) and elsewhere to ensure the long-term continuity of key environmental measurements in the long term. To achieve this goal, NASA will promote the convergence of the operational observation requirements of partner agencies with its research data needs for systematic observations, share the cost of new developments, and develop precursor instruments and spacecraft technologies for future operational application missions. NASA will also encourage the continuing involvement of scientific investigators in the calibration and validation of operational measurements, the development of more advanced information retrieval algorithms, and the analysis of operational data records. From this perspective, the potential for serving operational needs or commercial-applications is a priority criterion for NASA Earth science programs.

Interagency and international partnerships are also important for maximizing the scientific value of any research while minimizing costs. The need for partnerships in process-oriented field measurement activities is crucial, especially when investigators' access to particular regions of scientific interest is needed. For space-based measurements, partnerships provide the opportunity for leveraging additional contributions onto those that would be made by NASA, and allow for benefiting from the technological and scientific skills resident in other agencies and countries, as well as access to information needed for validation under a broad range of biological and geophysical conditions. Partnership opportunities will typically be encouraged in all relevant solicitations as long as they

are consistent with national policy objectives such as export control of sensitive technology. Commercial partnerships also provide the opportunity for NASA to obtain needed data or services, and NASA has committed to working with the private sector to avoid duplicating capability that already exists in it.

4.1.6 Technology Readiness

For observation projects in particular, a key criterion in determining the timing and order of selection is the readiness of the relevant technology. In some cases additional technological investments are required over the past and current years in order to demonstrate the possibility of making this measurement from space. For instance, lidar wind measurements were possible a decade ago, but only at an unacceptable cost for development and operations. Recent and ongoing work indicates the potential for design of a space-based system at a cost comparable to current programs, and perhaps even implementation as a commercial data purchase. NASA implements technology development programs relevant to each stage of the instrument maturation process (e.g., components, instrument design, flight demonstration). Parallel programs in spacecraft and information technologies are pursued to assure overall mission feasibility.

4.1.7 Program Balance

The hallmark of NASA's Earth science program is the synergy between different classes of observations, basic research, modeling, and data analysis, as well as field and laboratory studies. In particular, when engaging in pioneering research about complex scientific issues, the ESE recognizes the need for complementary remote sensing and in situ measurements. Nonetheless, the strategic decisions that define the ESE program in the long term are those, which affect the space flight mission element, involving the longest lead-time and largest investment of resources. From both a programmatic and a scientific research strategy perspective, the ESE distinguishes three types of space flight missions: systematic observation missions, exploratory missions, and operational precursor or technology demonstration missions. The identification of these categories represents a significant departure from the original architecture of the Earth Observing System, which combined studying basic processes, assembling long-term measurement records, and introducing innovative measurement techniques. The distinction between these classes of missions facilitates a sharper definition of primary mission requirements, and clearer selection criteria, ultimately leading to a shorter development cycle and more cost-effective implementation. Priority criteria will be considered separately for the research and analysis program and the separate categories of missions.

4.1.8 Cost/Budget Context

Ultimately NASA's budget constrains its Earth science research efforts. The suite of activities the agency undertakes must be consistent with budget lines. But financial resources depend on scientific rationale and societal benefit that derive from a balanced Earth Science program. Once established, the negotiated (or anticipated) budget becomes a criterion that may drive iteration for many projects back up the criterion ladder to some level.

4.2 National and International Planning, Coordination, and Collaboration

To address the broad requirements of numerous government, public, and private organizations around the world for improved Earth observations and understanding of the Earth system, NASA participates in an array of national and international planning and coordination activities related to Earth science and the environment. Much of NASA's Earth science research is focused on the goals and requirements of four major U.S. programs: (1) the Climate Change Science Program (CCSP), (2) the Climate Change Technology Program (CCTP), (3) the U.S. Weather Research Program (USWRP), and (4) Interagency Working Group on Earth Observations (IWGEO). These broad programs provide important frameworks for U.S. research addressing environmental change as well as for weather and natural hazard prediction.

U.S. Climate Change Science Program (CCSP). NASA Earth science research is aligned with the Climate Change Science Program involving 13 agencies seeking to address two fundamental questions:

- How will variability and potential change in climate and related systems affect natural environments and our way of life?
- How can we use and improve this knowledge to protect the global environment and to provide a better living standard for all?

To address these questions, the CCSP organizes long-term research within seven program elements: (1) Atmospheric Composition, (2) Climate Variability and Change, (3) Global Carbon Cycle, (4) Global Water Cycle, (5) Ecosystems, (6) Land Use or Land Cover Change, and (7) Human Contributions and Responses. Within NASA, Earth science research is organized under six focus areas corresponding closely with these CCSP program elements.

U.S. Weather Research Program (USWRP). The overarching goal of the USWRP is to improve high-impact weather forecasting capability at an accelerated pace. Particular emphasis is on better forecasts of the timing, location, and specific rainfall amounts of hurricanes and flood events that significantly affect the lives and property of U.S. inhabitants. Satellite observations, for example of tropical rainfall, are critical to reaching this goal as are improved systems for assimilating remote sensing data within models used for weather prediction.

U.S. Interagency Working Group on Earth Observations (IWGEO). A Declaration of the Earth Observation Summit of 33 nations and the European Commission in July, 2003 calls for a comprehensive, coordinated, and sustained Earth observing system or systems to: monitor continuously the state of the Earth; increase understanding of dynamic Earth processes; enhance prediction of the Earth system; and further implement environmental treaty obligations. Responding to this comprehensive goal, an intergovernmental Group on Earth Observations (GEO) is developing a 10 year plan for an integrated Earth observation system. The U.S. IWGEO coordinates the observing plans of U.S. Federal agencies and provides the U.S. input to the international GEO plan. NASA looks to this decadal planning activity to articulate many of the challenges and goals for the next major stages in Earth remote sensing, assimilation of observations, and prediction of variations and change within the Earth system.

NASA seeks mutually beneficial cooperation in Earth science research with other nations and groups of nations. In order to study the diverse components of global change, data with global scope and coverage are required. Phenomena across the planet must be observed, modeled, and understood. Regional observations and experiments as well as the participation of regional experts in the process of discovery are essential. Recognizing this inherently international character of Earth science, NASA has cooperative agreements for joint or coordinated Earth science research with over 60 nations that range from data sharing to collaborative development of remote sensing research satellites. Additionally, NASA participates in the major international programs in Earth science.

International Geosphere-Biosphere Programme (IGBP). With current focus on biogeochemistry, the IGBP delivers scientific knowledge to help human societies develop in harmony with Earth's environment. The program's scientific objective is to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth System, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions. IGBP develops and nurtures common international frameworks for collaborative research based on agreed agendas, assembles essential databases, and synthesizes scientific results.

World Climate Research Programme (WCRP). Jointly sponsored by the International Council of Scientific Unions and the World Meteorological Organization, WCRP develops the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of human influence on climate. The program encompasses studies of the global atmosphere, oceans, sea and land ice, and the land surface which together constitute the Earth's physical climate system.

Together with a number of other international programs and organizations, the IGBP and WCRP provide an important international framework within which NASA Earth science research participates for coordination, planning, and collaboration. NASA looks to IGBP and WCRP to provide forums for considering priorities and arranging cooperation in order to keep NASA Earth science research in synchrony with international efforts and those of specific regions and nations and to take maximum advantage of joint ventures.

5 Integration and Synthesis

The science focus areas enable NASA to tackle the Earth system science puzzle by arranging the problem in interdisciplinary yet implementable pieces which are themselves interconnected. Earth system science requires that we also bring the pieces back together.

Global and continuous observations from space combined with a comprehensive program of modeling, analysis, and synthesis enable the Earth system science research within NASA necessary to address challenging questions and issues of contemporary interest to society while extending our fundamental understanding of planet Earth. The Earth science focus areas provide the scientific basis for Earth observations and develop and maintain the research to resolve the science questions that underpin NASA's effort. Over the next decade, NASA will contribute far better capabilities for Earth observations and for projecting variations and change in the Earth system. Table 5.1 summarizes the major outcomes focusing on prediction that NASA expects to produce. Collectively, these outcomes represent a challenging decadal goal that requires unprecedented integration and synthesis of observations and the broad array of scientific results produced by research tasks within each focus area.

Many of the projected outcomes result from combining multiple observations, coupling models, and the synthesis of scientific results. Important properties and variables, such as the carbon content of soils, are not amenable to remote sensing and are better estimated from in situ measurements, where available, incorporated into models that are otherwise constrained over large areas by remote sensing. Assimilation of satellite observations into models provides a means of diagnosing the full states of major components of the Earth system, estimating current conditions for the entire system, and forecasting or predicting change. Satellite data assimi-

Table 5.1.

Projected Outcomes		
Climate Variability and Change	How can predictions of climate variability and change be improved?	Predict near- and long-term climate change, implications for global sea level change, regional temperature, precipitation, and soil moisture. For example by 2014: • Reduce uncertainty in global sea level rise by 50%; • Enable 10-year or longer climate forecasts.
Atmospheric Composition	How will future changes in atmospheric composition affect ozone, climate, and air quality?	Predict the course of recovery of Earth's atmospheric ozone shield and assess the air quality. For example by 2014: • Predict global distribution of stratospheric and tropospheric ozone to within 25%; • Enable extension of air quality forecasts for ozone and aerosols from 24 to 72 hours.
Carbon Cycle and Ecosystems	How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future?	Predict global terrestrial and oceanic biological productivity, ecosystem health, and interactions with the climate system. For example by 2014: • Project 10 to 100-year concentrations of CO_2 and CH_4 with greater than 50% improvement in confidence; • Enable ecological forecasts that project sensitivity of terrestrial and marine ecosystems.
Water and Energy Cycle	How will water and energy cycle dynamics change in the future?	Improve intermediate range forecasts for droughts and seasonal water supply; predict global scale energy storage and transport in the atmosphere. For example by 2014: • Enable seasonal precipitation forecasts at 10–100 km resolution with greater than 75% accuracy; • Balance global water and energy budgets to within 10%
Weather	How can weather forecast duration and reliability be improved?	Significantly improve short-term and severe weather forecasts for hurricanes, winter storm hazards, and other extreme weather events. For example by 2014: • Decreased hurricane landfall uncertainty from ± 100 km in 3-day forecasts; • Enable 7–10 day forecasts at 75% accuracy.
Earth Surface and Interior	How can our knowledge of Earth surface change be used to predict and mitigate natural hazards?	Predict volcanic activity within a month and estimate earthquake probabilities for selected tectonic zones. For example by 2014: • Enable 30-day volcanic eruption forecasts with greater than 50% confidence; • Estimation earthquake likelihood in North American plate boundaries with greater than 50% confidence.

lation for weather forecasting demonstrates the enormous potential of this approach.

Thus, as illustrated by figure. 5.1, NASA Earth science research is directed toward a fully coupled Earth system model constrained and driven by satellite observations. Incremental progress by coupling the models emerging from focus area research within a formal Earth system modeling framework enables important products along the path to a fully coupled model. For example, the dependence of the carbon cycle

Table 5.2a

U.S. Climate Change Science Program elements and NASA Earth science focus areas	
CCSP Research Elements	Earth Science Focus Areas
Atmospheric Composition	Atmospheric Composition
Climate Variability and Change	Climate Variability and Change
Global Water Cycle	Global Water and Energy Cyle
Land Use/Land Cover Change Global Carbon Cycle Ecosystems	Carbon Cycle and Ecosystems
Human Contributions and Response	
	Weather

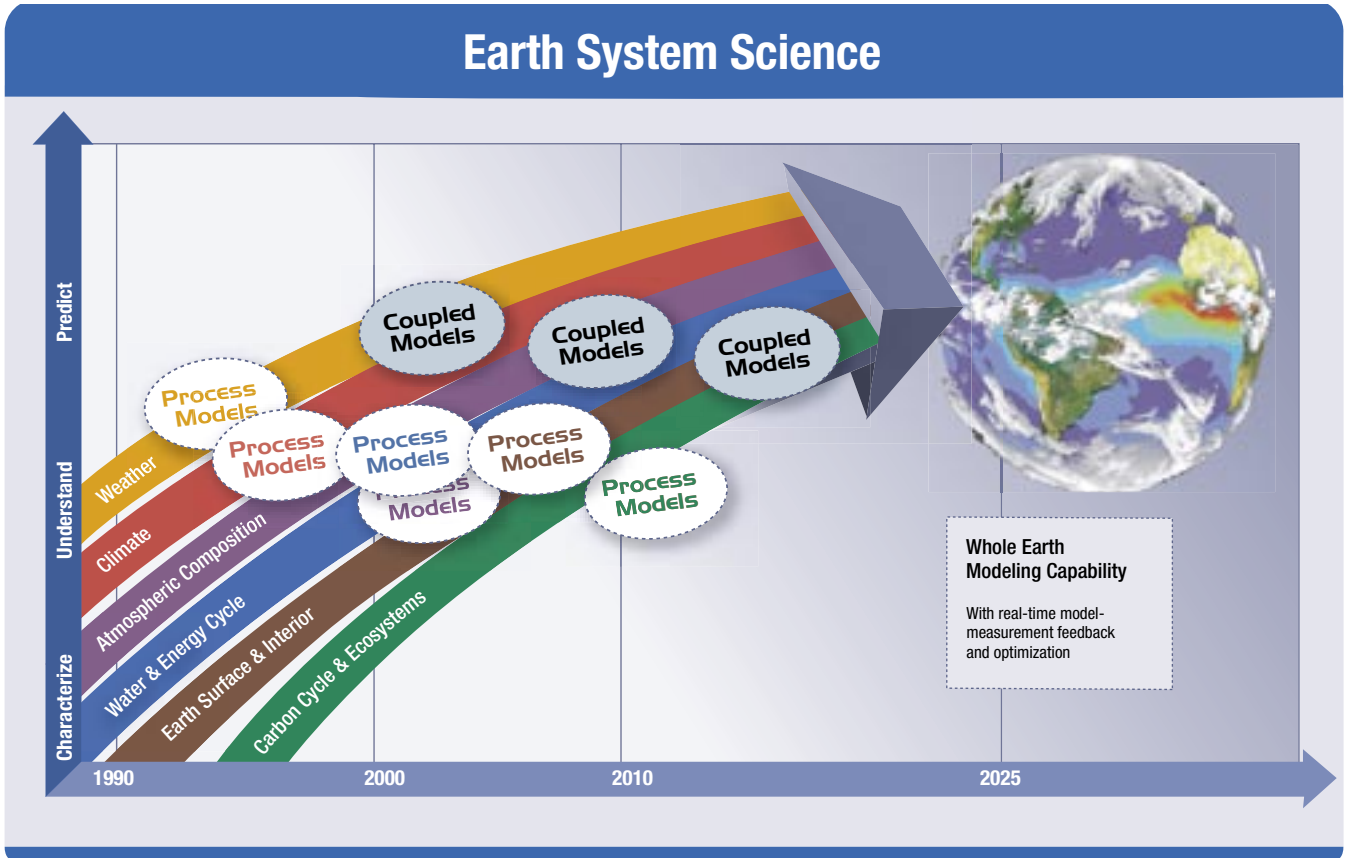
and climate systems on each other is so strong, that coupled models of these systems are being used now to provide better understanding of potential climate change due to CO_2 increase. These coupled carbon cycle and climate models will be improved further in the future by coupling to full atmospheric chemistry models in order to consider other atmospheric constituents or the shorter term influences of weather by incorporating weather phenomena.

NASA's goals in Earth science research, Earth observations, and Earth system modeling mandate coordination and collaboration with other Federal agencies. The U.S. Climate

Table 5.2b

U.S. Climate Change Science Program goals and NASA Earth science research questions	
CCSP Research Elements	Earth Science Research Questions
Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change	How is the global Earth system changing? (Variability)
Improve quantification of the forces bringing about changes in the Earth's climate and related systems	What are the primary causes of change in the Earth system? (Forcings)
Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future	How does the Earth system respond to natural and human-induced changes? (Response)
Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes	What are the consequences of change in the Earth system for human civilization? (Consequences)
Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change	How will the Earth system change in the future? (Prediction)

Figure 5.1



Change Science Program provides the framework for this co-operation toward resolving a suite of questions closely related to those in table 2.1, and NASA's Earth science focus areas are closely aligned with CCSP program elements (table 5.2a and b). The CCSP is committed to synthesis and assessment products, many of which will make use of Satellite observations and Earth system modeling results. Table 5.3 lists the products that NASA is directly responsible for, either in a lead or supporting role. Scientific results from all of NASA's Earth science focus areas will play in the CCSP synthesis; data products and model results aimed at decision support will be critical to producing assessment products.

Earth science research within NASA works in synergy with technology and education programs through constant interaction to introduce innovation and to continually revitalize the pool of talented scientists and engineers that will carry the program into yet unforeseen frontiers (figure. 5.2). The applied science program works to bring the wealth of observations and research results into decision support for nationally prominent topics. Companion plans describe the Education, Technology, and Applied Science Programs (figure. 1.2), taking guidance from this research plan and the Agency's overall Earth science strategy.

As figure 5.2 illustrates, the NASA Earth science program incorporates a critical cycle from research outcomes and their impacts back to the assumptions and questions underlying the research effort. New investigators and technological innovation are important drivers of this cycle. As we gain new knowledge and capabilities, new questions will replace those of today, and the current science focus areas will realign or perhaps be replaced to address new challenges. The research effort to address these questions will demand new observations, models, and analyses—the resources and tools of next generations of Earth system scientists.

Figure 5.2

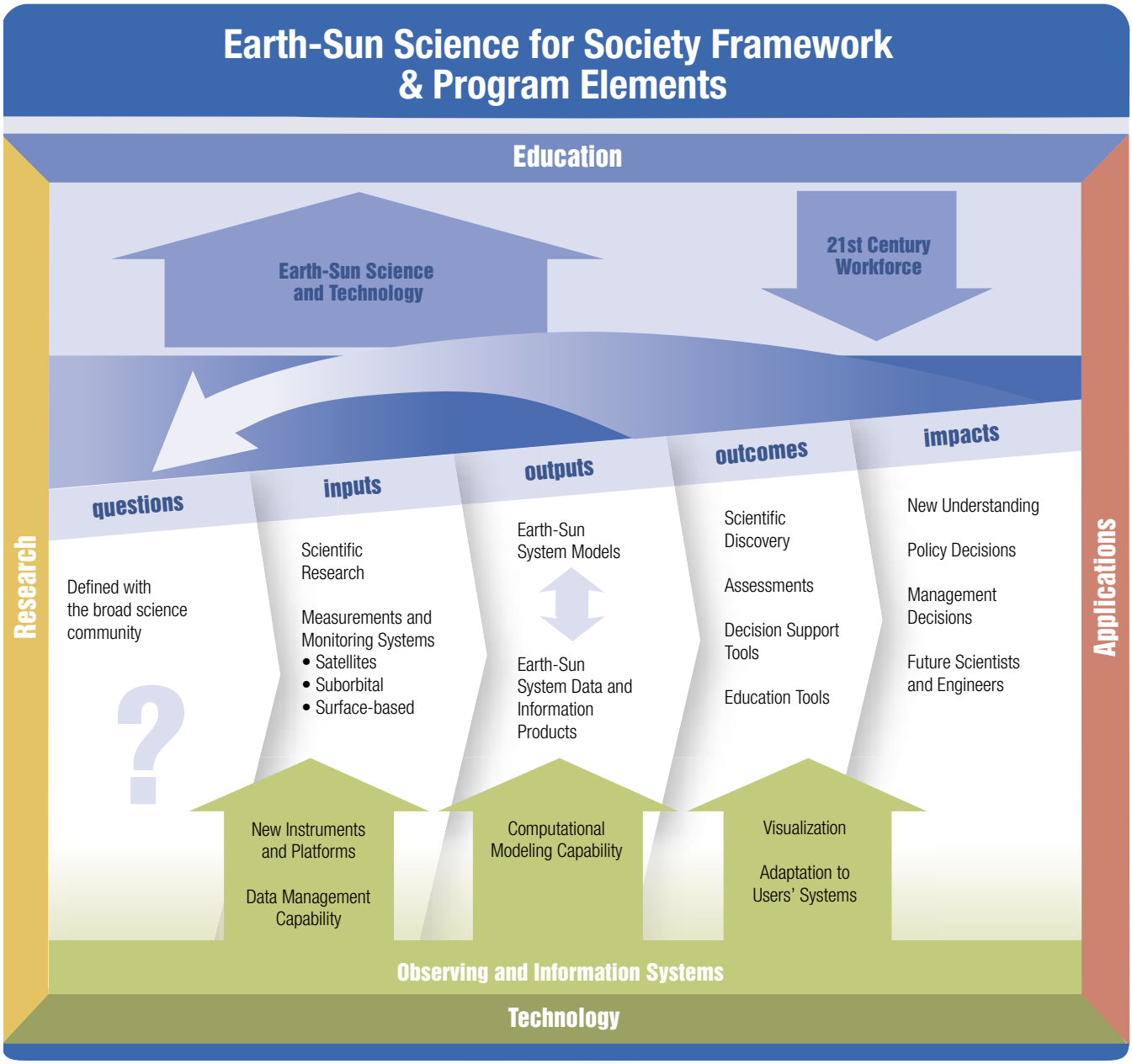

Earth-Sun Science for Society Framework
& Program Elements
Education
Earth-Sun Science
and Technology
21st Century
Workforce
questions
inputs
outputs
outcomes
impacts
Research
Applications
Defined with
the broad science
community
Scientific
Research
Measurements and
Monitoring Systems
• Satellites
• Suborbital
• Surface-based
Earth-Sun
System Models
Earth-Sun
System Data and
Information
Products
Scientific
Discovery
Assessments
Decision Support
Tools
Education Tools
New Understanding
Policy Decisions
Management
Decisions
Future Scientists
and Engineers
New Instruments
and Platforms
Data Management
Capability
Computational
Modeling Capability
Visualization
Adaptation to
Users' Systems
Observing and Information Systems
Technology

Table 5.3 U.S. Climate Change Science Program synthesis and assessment products.

Reference Number	Topic	Agencies	Time Frame (From October 2003)
1.1	Temperature Trends in the Lower Atmosphere—Steps for Understanding and Reconciling Differences	NOAA (Lead); NASA, DOE, NSF	Within 2 years
1.2	Past Climate Variability and Change in the Arctic and at High Latitudes	USGS (Lead); NSF, NOAA, NASA	Within 2 years
1.3	Re-analyses of Historical Climate Data for Key Atmospheric Features—Implications for Attribution of Causes of Observed Change	NOAA, NASA(Lead); DOE	2–4 years
2.1	Updating Scenarios of Greenhouse Gas Emissions and Concentrations in Collaboration with the CCTP—Review of Integrated Scenario Development and Application	DOE (Lead); NOAA, NASA	Within 2 years
2.2	North American Carbon Budget and Implications for the Global Carbon Cycle	DOE, NOAA, NASA (Lead); USDA, USGS	Within 2 years
2.3	Aerosol Properties and Their Impacts on Climate	NOAA, NASA (Lead)	2–4 years
2.4	Trends in Emissions of Ozone-Depleting Substances, Ozone Layer Recovery, and Implications for Ultraviolet Radiation Exposure and Climate Change	NOAA, NASA (Lead)	2–4 years
3.1	Climate Models and Their Uses and Limitations, Including Sensitivity, Feedbacks, and Uncertainty Analysis	DOE (Lead); NOAA, NASA, NSF	Within 2 years
3.3	Climate Extremes Including Documentation of Current Extremes—Prospects for Improving Projections	NOAA (Lead); NASA, USGS, DOE	2–4 years
4.1	Coastal Elevation and Sensitivity to Sea Level Rise	USGS, EPA, NOAA (Lead); NASA, DOE	Within 2 years
4.3	Relationship Between Observed Ecosystem Changes and Climate Change	USGS, USDA (Lead); EPA, NOAA, NASA, NSF, USGS, DOE, USAID	2–4 years
4.4	Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources	USDA, EPA (Lead); NOAA, NASA, USGS, DOE, USAID	2–4 years
4.5	Scenario-Based Analysis of the Climatological, Environmental, Resource, Technological, and Economic Implications of Different Atmospheric Concentrations of Greenhouse Gases	CCSP (Lead); NASA, USGS, EPA, NOAA, DOE	2–4 years
4.6	State-of-the-Science of Socioeconomic and Environmental Impacts of Climate Variability	EPA (Lead); NOAA, NASA, DOE, USAID	2–4 years
4.7	Within the Transportation Sector, a Summary of Climate Change and Variability Sensitivities, Potential Impacts, and Response Options	DOT (Lead); USGS, DOE, NASA	2–4 years

Table 5.3 Continued

Reference Number	Topic	Agencies	Time Frame (From October 2003)
5.1	Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected Sectors and Regions	NASA (Lead); EPA, NOAA, USGS, DOE	Within 2 years
5.2	Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Decision Making	NASA (Lead); EPA, NOAA, USGS, DOE, NSF	Within 2 years
5.3	Decision Support Experiments and Evaluations Using Seasonal to Interannual Forecasts and Observational Data	NOAA (Lead); NASA, EPA, USGS, USAID	Within 2 years

A Appendices

Appendix A

Observations for identifying Earth system variations and trends

Parameter	Implementation	Readiness	Operational Phase	Partnerships	Related In Situ
How are global precipitation, evaporation, and the cycling of water changing?					
Atmospheric Temperature	Passive sounding	Excellent	NPOESS	EUMETSAT coordination	Radiosondes (NOAA, WWW, NASA, NDSC)
	Active sounding (GPS)	Demonstration needed	NPOESS	EUMETSAT coordination	Global GPS network
Atmospheric Water Vapor	Passive sounding	Satisfactory	NPOESS	EUMETSAT coordination	Radiosondes, Ly- , µwave (NASA, NOAA, WWW)
Global Precipitation	Core radar satellite with 6–8 passive µwave satellite constellation	Demonstrated by TRMM and passive µwave imagers	Passive µwave	TRMM with Japan	Rain gauges, weather radar (NOAA, WWW)
Soil Moisture		Very large real or synthetic antenna to be demonstrated	Highly desired; subject to operational viability	Likely with European Space Agency	Neutron probes, lysimeters (USDA, USGS, FAO)
How is the global ocean circulation varying on interannual, decadal, and longer time scales?					
Ocean Surface Topography		Demonstrated. Development needed for denser coverage	Under study by NPOESS	Continuation of current partnerships likely	Tide gauges (Global Geodedic Network)
Ocean Surface Winds	Active/passive µwave	Demonstrated by NSCAT and Seawinds	NPOESS	Seawinds and follow-on with Japan	Ships, buoys (NOAA, WWW)
Sea Surface Temperature	IR and µwave	Excellent	NPOESS	EUMETSAT	Ships, buoys (NOAA, WWW)
Sea Ice Extent	µwave	Excellent	NPOESS	NASDA	Ships, airborne reconnaissance (Navy, USCG, NOAA)
How are global ecosystems changing?					
Terrestrial Primary Productivity	≤1 km resolution	Excellent MODIS	NPOESS	EUMETSAT	Inventory (USDA, FAO, NSF, GTOS)
Marine Primary Productivity		Demonstrated SeaWiFS, MODIS	NPOESS (Partial)	Japan and Europe (tentative)	SIMBIOS time series studies (NASA)
Classification,Functional Groups	Hyperspectral, Lidar	Demonstrated by EO-1 (Partial)	NPOESS (Partial) LDCM (Partial)	NOAA, USGS	Habitat structure, forest inventory, AUV, aircraft, moorings
How is atmospheric composition changing?					
Total Column Ozone		Excellent	NPOESS	EUMETSAT	Dobson, Brewer, FTIR, UV/VIS (NASA, NOAA)
Ozone Vertical Profile		Excellent	NPOESS	International coordination	Ozonesondes, Lidar, µwave , IR, (NASA, NOAA)

Appendix B

Observations for determining primary forcings on the Earth system

Parameter	Implementation	Readiness	Operational Phase	Partnerships	Related In Situ
What trends in atmospheric constituents and solar radiation are driving global climate?					
Total Solar Irradiance		Excellent	NPOESS		Global surface networks (BSRN, WRDC, SURFRAD)
Solar UV Irradiance		Excellent	NPOESS (planned)		USGCRP UV network, NDSC (multiagency)
Stratospheric Aerosol Distribution		Excellent	NPOESS (pending sufficient resolution)		Lidar, backscatter-sondes (NASA, NOAA, NSF)
Total Aerosol Amount		Excellent	NPOESS		AERONET, USDA network, NOAA/BSRN, DOE/ARM
Aerosol Properties		Further development needed		Important for ground-based measurements	AERONET, NOAA/CMDL, airborne aerosol spec-trometers
Surface Trace Gas Concentration		Simpler instruments with higher temporal resolution needed	AGAGE	Support ground network	NASA AGAGE, NOAA flask network
Volcanic Gas & Ash Emissions		Further development to characterize tropo-sphere constituents	Aviation requirements		Optical calibration
What changes are occurring in global land cover and land use, and what are their causes?					
Fire Occurrences	Global IR & visible or near IR; hyper-spec-tral for fuel load	Excellent MODIS,TRMM; EO-1 (Partial)	NPOESS, EDR application		Aeronet (NASA), burn scar inventory (USFS), optical calibration
Trace Gas Sources	CO_2 column mapping is greatest priority	OCO in definition phase	Not currently an operational require-ment		Flask network (NOAA), Ameriflux (DOE, USDA, NASA), FluxNet
Land Cover & Land Use	High spatial resolu-tion visible	Excellent Landsat; EO-1	LDCM	Commercial data purchase	Land Cover Maps (USGS), Vegetation Inventories (DOI, USDA)
What are the motions of the Earth's interior, and how do they directly impact our environment?					
Interior Motions of the Earth		Excellent	Multi-agency infrastructure	Exploratory missions	SLR, GPS, VLBI networks, magnetometer observations
What changes are occurring in the mass of the Earth's ice cover?					
Ice Surface Topography		ICEsat lidar altimetry demonstration		Coordination with European radar altimetry satellite	GPS (NASA, NSF)

Parameter	Implementation	Readiness	Operational Phase	Partnerships	Related In Situ
How is the Earth's surface being transformed by naturally occurring tectonic and climatic processes?					
Gravity Field		GRACE	DOD interests		Geodetic networks
How is the Earth's surface being transformed by naturally occurring tectonic and climatic processes?					
Terrestrial Reference Frame	Ground observation & precision satellite tracking	Excellent	Multi-agency infrastructure	Multi-national ground network	SLR and GPS networks
Surface Stress, Deformation	Focus on active earthquake & volcanic regions	Excellent	Local agency support of ground arrays	Multi-national ground arrays	Regional GPS networks, geological obsservations

Appendix C

Observations to characterize Earth system responses and feedbacks

Parameter	Implementation	Readiness	Operational Phase	Partnerships	Related In Situ
What are the effects of clouds and surface hydrologic processes on Earth's climate?					
Cloud System Structure	Multi-spectral visible & IR radiometry	Excellent	NOAA & NPOESS	EUMETSAT & Japanese ADEOS/GLI	Radiosondes, lidar (NASA, NOAA, FAA)
Cloud Particle Properties & Distribution	Active sensor to resolve 3-D structure	Demonstration of cloud radar and lidar pending			Altitude-resolved cloud particle data
Radiation Budget	Broadband radiometry	Excellent	NPOESS		Cloud and aerosol properties
Soil Moisture					neutron probes, lysimeters (USDA, USGS, FAO)
Snow Cover & Accumulation		Awaiting demonstration	NPOESS		Snow transects (NOAA/NWS)
Freeze-Thaw Transition		Awaiting demonstration			
How do ecosystems, land cover and biogeochemical cycles respond to and affect global environmental change?					
Terrestrial Biomass	Active sensor to resolve canopy structure	Awaiting demonstration			Crop-timber yields (USDA, DOI), carbon database (DOE)
Marine Biomass & Productivity		Excellent SeaWiFS, MODIS (Partial)	NPOESS (Partial)		Gliders, AUV's, moorings, floats (NASA, NOAA)
Carbon Sources and Sinks		OCO in definition phase			Flask network (NOAA), AmeriFlux/FluxNet (DOE, USDA, NASA)
How can climate variations induce changes in the global ocean circulation?					
Sea Surface Salinity	Very high radiometric precision passive μwave	Awaiting demonstration	NPOESS	European Space Agency	Ships and moored/drifting buoys (NOAA, NSF)
Sea Ice Thickness					Moored buoys (ONR)
How do atmospheric trace constituents respond to and affect global environmental change?					
Atmospheric Properties in Tropopause Region		Limb viewing sensors not yet demonstrated			Sondes (WWW, NOAA)
How is global sea level affected by natural variability and human-induced change in the Earth system?					
Polar ice sheet velocity	Synthetic aperture radar interferometry and image feature tracking	Demonstrated			GPS (NASA, NSF)

Appendix D

Observations for studying the consequences of Earth system change

Parameter	Implementation	Readiness	Operational Phase	Partnerships	Related In Situ
How are variations in local weather, precipitation and water resources related to global climate variation?					
Global Precipitation	Core radar satellite with 6–8 passive mwave satellite constellation	Demonstrated by TRMM and passive µwave imagers	Passive mwave	TRMM with Japan	Rain gauges, weather radar (NOAA, WWW)
Ocean Surface Winds	Active µwave	Demonstrated by NSCAT and SeaWinds		Seawinds cooperation with Japan; EUMETSAT	Ships, buoys (NOAA, WWW)
	Passive µwave radiometry/polarimetry	Windsat/Coriolis demonstration	NPOESS		N/A
Meteorological Properties Around Storms	Vertical profiling from a geostationary platform	Demonstration by GIFTS			Radiosondes (NOAA, WWW)
Lightning Rate	Geostationary	Demonstrated by OTD and LIS			Sferics (NOAA)
River Stage Height/ Discharge Rate		Capability demonstrated by Topex/Poseidon			River gauges (USGS)
What are the consequences of land cover and land use change for human societies and the sustainability of ecosystems?					
Primary Productivity	Global 1 km or better resolution needed	Excellent MODIS, Landsat	NPOESS LDCM	EUMETSAT	NASA-SIMBIOS, GOOS, GTOS, crop, forest inventories (USDA, FAO), LTER (NSF)
Land Cover/Land Use Change	High spatial resolution required	Excellent MODIS, (250m), Landsat, EO-1	LDCM NPOESS (Partial)	Commercial data sets	Land cover maps (USGS), vegetation inventories (DOI, USDA)
Functional Groups and Classification	Hyperspectral, Lidar	Moderate Demonstrated by EO-1 (Partial)	Partial by LDCM NPOESS	NOAA, USGS	Habitat structure, forest inventory, AUV, aircraft, moorings
What are the consequences of climate change and increased human activities for coastal regions?					
Coastal Region Properties and Productivity	Multispectral radiometry at high spatial and temporal resolution from GEO	Excellent			Coastal observations (NOAA, EPA)

Appendix E

Observations for predicting Earth system change

Parameter	Implementation	Readiness	Operational Phase	Partnerships	Related In Situ
How can weather forecast duration and reliability be improved?					
Tropospheric Winds	Active doppler lidar	Technical developments, demonstration needed		Commercial data purchase possible	Rawinsondes (NOAA, WWW)
Ocean Surface Winds	Active µwave	Demonstrated by NSCAT & SeaWinds		Seawinds cooperation with Japan; EUMETSAT	Ships, buoys (NOAA. WWW)
	Passive µwave radiometry/ polarimetry	Windsat/Coriolis demonstration	NPOESS		
Ocean Surface Salinity	Passive µwave radiometry	Aquarius in definition phase		Joint with Argentina	CTD, ARGO, XCTD
Cloud Microphysics	Polarimetric data	Demonstrated		NOAA, DOD	Aircraft sampling in field campaigns
Global Precipitation	6-8 satellite constellation	Demonstrated by TRMM & passive mwave imagers			Rain gauges, weather radar (NOAA, WWW)
Freeze-Thaw Transition		Awaiting demonstration			
Lightning Rate	Geostationary	Demonstrated by OTD and LIS			Sferics
Soil Moisture		Approaching readiness			Neutron probes, lysimeters (USDA, USGS, FAO)
Sea Surface Temperature	IR & µwave	Excellent	NPOESS	EUMETSAT coordination	Ships, buoys (NOAA, WWW)
How can predictions of climate variability and change be improved?					
Ocean Surface Topography	Non-polar orbit to avoid tidal aliasing	Demonstrated ; development needed for denser coverage	NPOESS (polar orbit is problematic)		Tide gauges; Global Geodetic Network for reference frame
Ocean Bottom Pressure & Topography	Enhanced satellite altimetry through better Topex tracks.	WOCE, GODAE research projects provide initial data base	Operational Global Ocean Observing System	Multi-agency, international cooperation is anticipated	Ships and ARGO floats (NOAA, NSF)
Ice Sheets	Lidar	Demonstrated			Mass balance
Sea-Ice Cover, Extent, Concentration and Thickness	Passive µwave, SAR scat, VIS/IR, altimetry	Very good in µwave and SAR, thickness requires demonstration		NOAA, DOD	Buoys, ice breakers, submarines
Ocean Heat		Demonstrated		NOAA	Deep sounding buoys

Parameter	Implementation	Readiness	Operational Phase	Partnerships	Related In Situ
How will future changes in atmospheric composition affect ozone, climate, and global air quality?					
Total Column Ozone		Excellent	NPOESS	EUMETSAT coordination	Dobson, Brewer, FTIR, UV/VIS (NASA, NOAA)
Aerosol		Good		EPA	Aeronet, sunphotometers, micro pulser lidar network
How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future?					
Trends in carbon sources and sinks	CO_2 and CH_4 column mapping	OCO for CO_2 in definition phase: CH_4 needs further development	Not currently and operational requirement		Flask network (NOAA), Ameriflux/FluxNet (DOE, USDA, NASA)
Surface Properties & Primary Productivity	High spatial resolution	Excellent, Lidar, InSAR, and optical need development and need to reduce cost. MODIS, Landsat	Partially by NPOESS	Commercial data purchase possible; ESA, JAXA, CSA; EUMETSAT coordination	Land cover maps (USGS), Vegetation inventories (DOI, USDA)
Trends in biomass	Lidar, radar	Awaiting demonstration			Crop, forest inventory (USDA, FAO, NSF, GTOS); Ameriflux/Flux Net (DOE, USDA, NASA); SIMBIOS
Functional Groups and Classification	Hyper-spectral, Lidar	Demonstrated by EO-1	Partially provided by NPOESS, LDCM	NOAA, USGS	Habitat structure, forest inventory, AUV, aircraft, moorings
How can our knowledge of earth surface change be used to predict and mitigate natural hazards?					
Surface Deformation	InSAR with 1 mm/yr surface displacement	Good/awaiting demonstration		NSF	GPS, seismology, borehole strain (NASA/NSF/USGS)
High-Resolution Topography	SRTM data, imaging lidar; data sets, German X-SAR and optical data e.g., ASTER, and ERS-1/2 tandem mission	Technology development for space-based lidar, formation flying InSAR at L Band		USGS, NIMA	
Earth's Magnetic Field		Good		Excellent-NIMA, Europeans ESA, DLR, DSRI, CONAE, ASI, ISA	Intermagnet ground network
Earth's Gravity Field	GRACE and CHAMP analysis	Good	ESA GOCE	ESA, DLR, NIMA	Ocean bottom and atmospheric pressure essential