

## **Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation**

Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, National Research Council

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# EARTH SCIENCE AND APPLICATIONS FROM SPACE

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URGENT NEEDS AND OPPORTUNITIES TO SERVE THE NATION

Committee on Earth Science and Applications from Space:  
A Community Assessment and Strategy for the Future

Space Studies Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL  
*OF THE NATIONAL ACADEMIES*

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*COVER:* Global radar measurements from the SeaWinds scatterometer on the QuikSCAT satellite provide scientists and weather forecasters with information on surface wind speed and direction. Scientists also use the radar measurements directly to learn about changes in vegetation and ice extent over land and polar regions. This false-color image is based entirely on SeaWinds measurements obtained over oceans, land, and polar regions. Over the ocean, colors indicate wind speed, with orange as the fastest wind speeds and blue as the slowest. White streamlines indicate the wind direction. The ocean winds in this image were measured by SeaWinds on September 20, 1999. The large storm in the Atlantic off the coast of Florida is Hurricane Gert. Tropical storm Harvey is evident as a high-wind region in the Gulf of Mexico, while farther west in the Pacific is tropical storm Hilary. An extensive storm is also present in the South Atlantic Ocean near Antarctica. The land image was made from 4 days' worth of SeaWinds data with the aid of a resolution enhancement algorithm developed by David Long at Brigham Young University. Further information about this image is available at <[http://winds.jpl.nasa.gov/publications/pacific\\_global\\_winds\\_5.cfm](http://winds.jpl.nasa.gov/publications/pacific_global_winds_5.cfm)>.

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<sup>1</sup>The committee notes with deep regret Aram Mika's death on May 18, 2005.

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## Preface

In response to requests from NASA, NOAA, and the USGS, the National Research Council has begun a decadal survey of Earth science and applications from space. Developed in consultation with members of the Earth science community, the guiding principle for the study is to set an agenda for observations in support of Earth science and applications from space in which attaining practical benefits for humankind plays a role equal to that of acquiring vitally important new knowledge about our planet.<sup>1</sup> These benefits may range from access to information that can satisfy short-term needs for weather warnings for the protection of life and property, to the development of longer-term scientific understanding that is the lifeblood of future societal applications, the details of which are not predictable.

Among the key tasks in the charge to the Committee on Earth Science and Applications from Space are the requests to:

- Develop a consensus on the top-level scientific questions that should provide the focus for Earth and environmental observations in the period 2005-2015; and
- Develop a prioritized list of recommended space programs, missions, and supporting activities to address these questions.

The committee's final report, expected in late 2006, will address these tasks as well as the others described in Appendix A.<sup>2</sup> The purpose of this brief interim report, which was requested by the sponsors of the study and by members of congressional staff, is to provide an early indication of urgent, near-term issues that require attention prior to publication of the committee's final report.

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<sup>1</sup>Development of the vision for the study drew on information received in response to a widely distributed request for comments; town-hall style discussions at the December 2004 meeting in San Francisco of the American Geophysical Union and the January 2005 meeting in San Diego of the American Meteorological Society; committee discussions at a workshop held on August 23-25, 2004, in Woods Hole, Mass.; and discussions at two committee meetings held on November 8-9, 2004, in Washington, D.C., and January 4-6, 2005, in Irvine, Calif.

<sup>2</sup>The final report will also draw on the work of seven study panels organized according to the following themes to address all of the elements of the statement of task (see Appendix A): (1) Earth science applications and societal needs, (2) ecosystem health and biodiversity, (3) weather (including chemical and space weather), (4) climate variability and change, (5) water resources and the global hydrologic cycle, (6) human health and security, and (7) solid-Earth hazards, resources, and dynamics.



## Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Judith Curry, Georgia Institute of Technology,  
Lennard A. Fisk, University of Michigan,  
Christopher O. Justice, University of Maryland,  
Pamela A. Matson, Stanford University,  
Norine E. Noonan, College of Charleston,  
David T. Sandwell, Scripps Institution of Oceanography, and  
Paul D. Try, Science and Technology Corporation.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Carl Wunsch, Massachusetts Institute of Technology, and Robert A. Frosch, Harvard University. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

# Contents

EXECUTIVE SUMMARY	1
1 SCIENCE FOR THE BENEFIT OF SOCIETY	9
2 EARTH OBSERVATIONS AND PRESIDENTIAL INITIATIVES	13
3 CRITICAL NEEDS FOR TODAY	16
Proceed with GPM and GIFTS, 18	
Evaluate Plans for Transferring Needed Capabilities to NPOESS, 19	
Develop a Technology Base for Future Earth Observation, 23	
Reinvigorate the NASA Earth Explorer Missions Program, 25	
Strengthen Baseline Climate Observations and Climate Data Records, 27	
4 SUMMARY AND NEXT STEPS	32
APPENDIXES	
A Statement of Task	35
B Acronyms and Abbreviations	37
C Biographies of Committee Members and Staff	39



# Executive Summary

*Understanding the complex, changing planet on which we live, how it supports life, and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity. It is also one of the most important for society as it seeks to achieve prosperity and sustainability.*

The decades of the 1980s and 1990s saw the emergence of a new paradigm for understanding our planet—observing and studying Earth as a system of interconnected parts including the land, oceans, atmosphere, biosphere, and solid Earth. At the same time, satellite observing systems came of age and produced new and exciting perspectives on Earth and how it is changing. By integrating data from these new observation systems with in situ observations, scientists were able to make steady progress in the understanding of and ability to predict a variety of natural phenomena, such as tornadoes, hurricanes, and volcanic eruptions, and thus help mitigate their consequences. Decades of investments in research and the present Earth observing system have also improved health, enhanced national security, and spurred economic growth by supplying the business community with critical environmental information.

Yet even this progress has been outpaced by society's ongoing need to apply new knowledge to expand its economy, protect itself from natural disasters, and manage the food and water resources on which its citizens depend. The aggressive pursuit of understanding Earth as a system—and the effective application of that knowledge for society's benefit—will increasingly distinguish those nations that achieve and sustain prosperity and security from those that do not. In this regard, recent changes in federal support for Earth observation programs are alarming. At NASA, the vitality of Earth science and application programs has been placed at substantial risk by a rapidly shrinking budget that no longer supports already-approved missions and programs of high scientific and societal relevance. Opportunities to discover new knowledge about Earth are diminished as mission after mission is canceled, descope, or delayed because of budget cutbacks, which appear to be largely the result of new obligations to support flight programs that are part of the Administration's vision for space exploration. In addition, transitioning of many of the scientific successes at NASA into operational capabilities at NOAA and other agencies has failed to materialize, years after the potential and societal needs were demonstrated, even as the United States has

announced that it will take a leadership role in international efforts to develop integrated, global observing systems.

The Committee on Earth Science and Applications from Space affirms the imperative of a robust Earth observation and research program to address such profound issues as the sustainability of human life on Earth and to provide specific benefits to society. Achieving these benefits further requires that the observation and science program be closely linked to decision support structures that translate knowledge into practical information matched to and cognizant of society's needs. The tragic aftermath of the 2004 Asian tsunami, which was detected by in situ and space-based sensors that were not coupled to an appropriate warning system in the affected areas of the Indian Ocean, illustrates the consequences of a break in the chain from observations to the practical application of knowledge.

The committee's vision for the future is clear: The nation needs to rise to the grand challenge of effectively enhancing and applying scientific knowledge of the Earth system both to increase fundamental understanding of our home planet and how it sustains life and to meet increasing societal needs. This vision reflects and supports established national and international objectives, built around the presidential directives that guide the U.S. climate and Earth observing system initiatives. Realizing the vision requires a strong, intellectually driven Earth sciences program and an integrated in situ and space-based observing system—the foundation essential to developing knowledge of Earth, predictions, and warnings—as well as better decision-support tools to transform new knowledge into societal benefits and more effectively link science to applications. The payoff for our nation and for the world is enormous.

### EARTH OBSERVATION TODAY

The current U.S. civilian Earth observing system centers on the environmental satellites operated by NOAA;<sup>1</sup> the atmosphere-, biosphere-, ocean-, ice-, and land-observation satellites of NASA's Earth Observing System (EOS);<sup>2</sup> and the Landsat satellites, which are currently managed under a cooperative arrangement involving NASA and the U.S. Geological Survey (USGS). Today, this system of environmental satellites is at risk of collapse. Although NOAA has plans to modernize and refresh its weather satellites, NASA has no plan to replace its EOS platforms after their nominal 6-year lifetimes end (beginning with the Terra satellite in 2005), and it has canceled, descoped, or delayed at least six planned missions, including the Landsat Data Continuity "bridge" mission.<sup>3</sup>

These decisions appear to be driven by a major shift in priorities at a time when NASA is moving to implement a new vision for space exploration. This change in priorities jeopardizes NASA's ability to fulfill

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<sup>1</sup>See discussion at the NOAA Web site at <<http://www.nesdis.noaa.gov/satellites.html>>.

<sup>2</sup>EOS is composed of a series of satellites, a science component, and a data system supporting a coordinated series of polar-orbiting and low-inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans. See "The Earth Observing System," at <<http://eospsa.gsfc.nasa.gov/>>.

<sup>3</sup>In accordance with congressional guidance and the Land Remote Sensing Policy Act of 1992 (PL 102-555), the Commercial Space Act of 1998 (PL 105-303), and the U.S. Commercial Remote Sensing Policy (April 25, 2003), NASA and the Department of the Interior/USGS initially planned to continue the Landsat-7 data series by implementing a Landsat Data Continuity Mission (LDCM) that would procure data from a privately owned and commercially operated remote sensing system. Following an evaluation of proposals, NASA declined to accept any offers and canceled this plan in September 2003. Per guidance from the White House Office of Science and Technology Policy, NASA then agreed to transition Landsat measurements to an operational environment through the incorporation of Landsat-type sensors on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) platform. NASA also agreed to further assess options to mitigate the risks to data continuity prior to the first NPOESS-Landsat mission, including a "bridge" mission. Unless otherwise specified, the committee's reference to cancellation of the LDCM is to this bridge or "gap filler" option, which would have launched a free-flying instrument to avoid a gap in data continuity between the already-degraded Landsat 7 and the launch of the first NPOESS-Landsat satellite in late 2009 or early 2010.

its obligations in other important presidential initiatives, such as the Climate Change Research Initiative and the subsequent Climate Change Science Program. It also calls into question future U.S. leadership in the Global Earth Observing System of Systems, an international effort initiated by the current Administration. The nation's ability to pursue a visionary space exploration agenda depends critically on its success in applying knowledge of Earth to maintain economic growth and security at home.

Moreover, a substantial reduction in Earth observation programs today will result in a loss of U.S. scientific and technical capacity, which will decrease the competitiveness of the United States internationally for years to come. U.S. leadership in science, technology development, and societal applications depends on sustaining competence across a broad range of scientific and engineering disciplines that include the Earth sciences.

As a result of the recent mission cancellations, budget-induced delays, and mission descopes, the committee finds the existing Earth observing program to be severely deficient. The near-term recommendations presented below describe the minimum set of actions needed to maintain the health of the NASA scientific and technical programs until more comprehensive community recommendations are made in the final report of the survey. They address deficiencies in the current program at NASA and some of the emerging needs of NOAA and the USGS. The committee's recommendations address issues in six interrelated areas:

1. Canceled, descoped, or delayed Earth observation missions;
2. Prospects for the transfer of capabilities from some canceled or descoped NASA missions to NPOESS;
3. The adequacy of the technological base for future missions;
4. The status and future prospects of NASA Earth science Explorer-class missions;
5. The adequacy of research and analysis programs to support future programs; and
6. Development of baseline climate observations and data records.

### **ACTIONS TO MEET CURRENT CRITICAL NEEDS**

#### **Proceed with GPM and GIFTS**

Recently, six NASA missions with clear societal benefits and the established support of the Earth science and applications community have been delayed, descoped, or canceled. Two of these missions should proceed immediately:

- *Global Precipitation Measurement (GPM)*. The Global Precipitation Measurement mission is an international effort to improve climate, weather, and hydrological predictions through more accurate and more frequent precipitation measurements. GPM science will be conducted through an international partnership led by NASA and the Japan Aerospace Exploration Agency (JAXA). Water cycling and the availability of fresh water resources, including their predicted states, are of critical concern to all nations, and precipitation is the fundamental driver of virtually all water issues, including those concerned with national security. GPM is the follow-on to the highly successful Tropical Rainfall Measuring Mission, which is nearing the end of operations.<sup>4</sup> It is an approved mission that has been delayed several times by NASA.

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<sup>4</sup>National Research Council, *Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission: A Perspective from the Research and Operations Communities, Interim Report*, The National Academies Press, Washington, D.C., 2005, in press.

**The committee recommends that the Global Precipitation Measurement mission be launched without further delays.**

- *Atmospheric Soundings from Geostationary Orbit (GIFTS)*. The Geostationary Imaging Fourier Transform Spectrometer (GIFTS) will provide high-temporal-resolution measurements of atmospheric temperature and water vapor, which will greatly facilitate the detection of rapid atmospheric changes associated with destructive weather events, including tornadoes, severe thunderstorms, flash floods, and hurricanes. The GIFTS instrument has been built at a cost of approximately \$100 million, but the mission has been canceled for a variety of reasons. However, there exists an international opportunity to launch and test GIFTS.

**The committee recommends that NASA and NOAA complete the fabrication, testing, and space qualification of the GIFTS instrument and that they support the international effort to launch GIFTS by 2008.**

Three other missions—Ocean Vector Winds, Landsat Data Continuity, and Glory—as well as development of enabling technology such as the now-canceled wide-swath ocean altimeter, should be urgently reconsidered, as described below.

#### **Evaluate Plans for Transferring Needed Capabilities to NPOESS**

Instruments on the following three canceled missions may be either reinstated as independent NASA missions as originally planned or replaced with appropriate instruments for flight on the National Polar-orbiting Operational Environmental Satellite System (NPOESS). This latter approach has both advantages (e.g., transfer of research capabilities to operational use) and disadvantages (e.g., decrease in instrument capability, gaps in data continuity).

- *Ocean Vector Winds*. Global ocean surface vector wind observations have enhanced the accuracy of severe storm warnings, including hurricane forecasts, and have improved crop planning as a result of better El Niño predictions. Such observations are achievable from proven space-borne scatterometer systems. However, NASA has canceled the Ocean Vector Winds mission, a previously planned follow-on to the active scatterometer currently operating on the QuikSCAT mission, which has already exceeded its design life. NOAA is currently planning to use a *passive* microwave sounder, CMIS (Conical Scanning Microwave Imager/Sounder), which will be launched on NPOESS, to recover ocean wind measurements. Tests of the feasibility of this technique are underway based on use of a similar instrument on the Navy's Windsat satellite.

- *Landsat Data Continuity*. For more than 30 years, Landsat satellites have collected data on Earth's continental surfaces to support Earth science research and state and local government efforts to assess the quality of terrestrial habitats, their resources, and their changes due to human activity. These data constitute the longest continuous record of Earth's surface as seen from space. The Land Remote Sensing Policy Act of 1992 directs NASA and the USGS to assess various system development and management options for a satellite system to succeed Landsat 7. The president's budget for NASA for FY 2006 discontinues plans for launch of this satellite system and instead directs NASA to assume responsibility for providing two Operational Land Imager (OLI) instruments for delivery to NPOESS (the second OLI is to be delivered 2 years after the first).

- *Glory*. Glory carries two instruments—the Advanced Polarimetric Sensor (APS) and the Total Irradiance Monitor (TIM). Part of the framework of the president's Climate Change Research Initiative, Glory was developed to measure aerosol properties (via the APS) with sufficient accuracy and coverage to quantify



the effect of aerosols on climate. Aerosol forcing is one of the most important sources of uncertainty in climate prediction. Glory would also monitor the total solar irradiance. Measurements of total solar irradiance are needed to understand how the Sun's energy output varies and how these variations affect Earth's climate. TIM would ensure continuity of this important time-series should the irradiance monitor on the Solar Radiation and Climate Experiment (SORCE) satellite fail prior to the launch of NPOESS.

**The committee recommends that NASA, NOAA, and the USGS commission three independent reviews, to be completed by October 2005, regarding the Ocean Vector Winds, Landsat Data Continuity, and Glory missions.<sup>5</sup> These reviews should evaluate:**

- **The suitability, capability, and timeliness of the OLI and CMIS instruments to meet the research and operational needs of users, particularly those that have relied on data from Landsat and QuikSCAT;**
- **The suitability, capability, and timeliness of the APS and TIM instruments for meeting the needs of the scientific and operational communities;**
- **The costs and benefits of launching the Landsat Data Continuity and Glory missions prior to or independently of the launch of the first NPOESS platform; and**
- **The costs and benefits of launching the Ocean Vector Winds mission prior to or independently of the launch of CMIS on NPOESS.**

**If the benefits of an independent NASA mission(s) cannot be achieved within reasonable costs and risks, the committee recommends that NASA build the OLI (two copies, one for flight on the first NPOESS platform<sup>6</sup>), APS, and TIM instruments and contribute to the costs of integrating them into NPOESS. APS, TIM, and the first copy of OLI should be integrated onto the first NPOESS platform to minimize data gaps and achieve maximum utility.**

The reviews could be conducted under the auspices of NASA and NOAA and USGS external advisory committees or other independent advisory groups and should be carried out by representative scientific and operational users of the data, along with NOAA and NASA technical experts.

### **Develop a Technology Base for Future Earth Observation**

Much of the recent progress in understanding Earth as an integrated system has come from NASA's EOS, which is composed of three multi-instrumented platforms (Terra, Aqua, and Aura) and associated smaller missions.<sup>7</sup> Initial plans, made in the 1980s, called for three series of each of the platforms to ensure a 15-year record of continuous measurements of the land surface, biosphere, solid Earth, atmosphere, and oceans. However, by the late 1990s, budget constraints and other factors led NASA to abandon plans for follow-ons to the first series of EOS satellites. Knowledge anticipated from analysis of EOS long-term data records depends now on a precarious plan to use instruments on the nation's next generation of operational weather satellites—NPOESS, scheduled for launch in 2009, and a new GOES series, scheduled for

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<sup>5</sup>Note added in proof: Wording corrected to include the USGS, which was inadvertently omitted in the prepublication copy of this report.

<sup>6</sup>The Landsat Data Continuity mission called for the procurement of two instruments, each with a mission lifetime of 5 years, to provide continuity to the Landsat 7 data set.

<sup>7</sup>NASA's Mission to Planet Earth (MTPE) began as an attempt to monitor the entire Earth and continuously evaluate global change trends. In effect, MTPE was a program to evaluate the sustainability of human life on Earth via a study of the interrelated and complex processes involving Earth's geosphere, atmosphere, hydrosphere, and biosphere. The space-based component of MTPE, the Earth Observing System (EOS), was the centerpiece of MTPE; it began formally in the early 1990s.



launch in 2012—foreign missions, and the occasional launch of small Explorer-class missions. In fact, aside from several delayed Explorer-class missions, the Ocean Surface Topography Mission (a follow-on to the current Jason-1 mission), and the Global Precipitation Measurement mission, the NASA program for the future has no explicit set of Earth observation mission plans.

The committee's final report will include a prioritized list of new Earth observing missions and capabilities. In the meantime, a healthy scientific and technological base for future missions must be maintained.

- *Enabling technology base.* The paucity of missions in active planning mode undercuts the observational capability for which a strong enabling technology base is essential. Particularly disturbing is the absence of development activities for identified measurement capabilities that have been extensively studied, vetted within the community, and endorsed by NASA. For example, interferometric synthetic aperture radar (InSAR) technology now exists in Europe and Canada to monitor small changes in Earth's surface that might presage a volcanic eruption or an earthquake, but development of L-band technology will be required to overcome the limitations of current instruments for observing in vegetated areas. Radar interferometry (wide-swath altimetry) was also being developed to monitor coastal currents, eddies, and tides, which affect fisheries, navigation, and ocean climate, but a planned mission was canceled. Finally, the European Space Agency plans to launch in 2008 a mission to measure winds in the atmosphere using an ultraviolet laser, but in the United States active remote sensing techniques for such measurements are not yet at a comparable level of technology readiness.

**The committee recommends that NASA significantly expand existing technology development programs to ensure that new enabling technologies for critical observational capabilities, including interferometric synthetic aperture radar, wide-swath ocean altimetry, and wind lidar, are available to support potential mission starts over the coming decade.**

### **Reinvigorate the NASA Earth Explorer Missions Program**

NASA developed its Earth System Science Pathfinder (ESSP) program as “an innovative approach for addressing Global Change Research by providing periodic ‘Windows of Opportunity’ to accommodate new scientific priorities and expand community participation in NASA Earth science activities. The program is characterized by relatively low to moderate cost, small to medium sized missions that are capable of being built, tested and launched in a short time interval.”<sup>8</sup> ESSP missions were intended to be launched at a rate of one or more per year.

ESSP missions provide a mechanism for developing breakthrough science and technology that enables future societal benefits and for ensuring that human capital is maintained for future missions. For example, the Gravity Recovery and Climate Experiment (GRACE) mission measured time-varying gravity changes up to 100,000 times smaller than those measured previously and provided the first measurements of variations in groundwater storage at continental scales.<sup>9</sup> New ESSP missions within this program need to be initiated on a frequent basis to fuel innovation,<sup>10</sup> and missions must be launched soon after selection to keep the

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<sup>8</sup>See information on the Earth System Science Pathfinder program at <<http://earth.nasa.gov/essp/>>.

<sup>9</sup>See M. Cheng and B.D. Tapley, 2004, “Variations in the Earth's Oblateness During the Past 28 Years,” *JGR-Solid Earth* 109(N9): B09402. Also see “GRACE Science Papers” on the GRACE home page at <<http://www.csr.utexas.edu/grace/publications/papers/>>.

<sup>10</sup>This approach corresponds to the original intent of the Earth System Science Pathfinder program, which solicited proposals every 2 years for satellite measurements that were outside the scope of approved Earth science missions. Proposals were solicited in all Earth science disciplines, from which two missions and one alternate were selected based on scientific priority and technical readiness.

technology from becoming obsolete. Some of the missions now being planned may not be launched until nearly 10 years after they were selected.

**The committee supports continuation of a line of Explorer-class missions directed toward advancing understanding of Earth and developing new technologies and observational capabilities, and urges NASA to:**

- **Increase the frequency of Explorer selection opportunities and accelerate the ESSP-3 missions by providing sufficient funding for at least one launch per year, and**
- **Release an ESSP-4 announcement of opportunity in FY 2005.**

### **Strengthen Research and Analysis Programs**

The committee is concerned that a significant reallocation of resources for the research and analysis (R&A)<sup>11</sup> programs that sustain the interpretation of Earth science data has occurred either as a result of the removal of the “firewall” that previously existed between flight and science programs or as an unintended consequence of NASA’s shift to full-cost accounting. Because the R&A programs are carried out largely through the nation’s research universities, there will be an immediate and deleterious impact on graduate student, postdoctoral, and faculty research support. The long-term consequence will be a diminished ability to attract and retain students interested in using and developing Earth observations. Taken together, these developments jeopardize U.S. leadership in both Earth science and Earth observations, and they undermine the vitality of the government-university-private sector partnership that has made so many contributions to society.

### **Strengthen Baseline Climate Observations and Climate Data Records**

The nation continues to lack an adequate foundation of climate observations that will lead to a definitive knowledge about how climate is changing and will provide a means to test and systematically improve climate models. NASA and NOAA should enhance their observing systems to ensure that there are long-term, accurate, and unbiased benchmark climate observations.

**The committee recommends that NASA, NOAA, and other agencies as appropriate accelerate efforts to create a sustained, robust, integrated observing system that includes at a minimum an essential baseline of climate observations, including atmospheric temperature and water vapor, spectrally resolved Earth radiances, and incident and reflected solar irradiance.**

Finally, as recommended in previous National Research Council reports, an expanded set of long-term, accurate climate data records should continue to be produced to monitor climate variability and change. A climate data and information system for NPOESS is needed that will make it possible to assemble relevant observations, remove biases, and distribute and archive the resulting climate data records. A

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<sup>11</sup>R&A has customarily supplied funds for enhancing fundamental understanding in a discipline and stimulating the questions from which new scientific investigations flow. R&A studies also enable conversion of raw instrument data into fields of geophysical variables and are an essential component in support of the research required to convert data analyses to trends, processes, and improvements in simulation models. They are likewise necessary for improving calibrations and evaluating the limits of both remote and in situ data. Without adequate R&A, the large and complex task of acquiring, processing, and archiving geophysical data would go for naught. Finally, the next generation of Earth scientists—the graduate students in universities—are often educated by performing research that has originated in R&A efforts. See National Research Council, *Earth Observations from Space: History, Promise, and Reality (Executive Summary)*, National Academy Press, Washington, D.C., 1995.

corresponding research and analysis effort is also needed to understand what these records indicate about how Earth is changing.

**The committee recommends that NOAA, working with the Climate Change Science Program and the international Group on Earth Observations, create a climate data and information system to meet the challenge of ensuring the production, distribution, and stewardship of high-accuracy climate records from NPOESS and other relevant observational platforms.**

Today the nation's Earth observation program is at risk. If we succeed in implementing the near-term actions recommended above and embrace the challenge of developing a long-term observation strategy that effectively recognizes the importance of societal benefits, a strong foundation will be established for research and operational Earth sciences in the future, to the great benefit of society—now and for generations to come.

# 1

## Science for the Benefit of Society

*The Earth's well-being is also an issue important to America. And it's an issue that should be important to every nation in every part of our world.*

—President George W. Bush discussing climate change on June 11, 2001<sup>1</sup>

Progress in Earth science over the last two decades has been dramatic, a consequence of decisions made in the 1980s to study Earth as a system.<sup>2</sup> Research in Earth system science has led to remarkable insights and new lines of inquiry based on how Earth's atmosphere, oceans, and land interact and evolve as a whole to sustain life. How Earth will continue to change in the future and what these changes will mean to society are scientific questions of profound importance.

Improved scientific understanding of Earth also forms the foundation for practical applications that enhance the prosperity and security of society. Businesses, government agencies, and even individuals rely on products and services that have emerged from Earth science research programs. For example, improvements in the ability to forecast weather (Box 1.1) have had an enormous impact on society. Today's 4-day weather forecast is as accurate as 2-day forecasts were 20 years ago.<sup>3</sup> The error in the 3-day forecast landfall position of hurricanes has been reduced from about 210 miles in 1985 to about 110 miles in 2004.<sup>4</sup> Sea surface winds and precipitation can be observed at accuracies that allow emergency managers to more efficiently evacuate coastal residents in the path of hurricanes. As a result, lives are saved and property losses are minimized. Increased knowledge about the ocean-atmosphere-land system suggests

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<sup>1</sup>See <<http://www.whitehouse.gov/news/releases/2001/06/20010611-2.html>>.

<sup>2</sup>For example, the report that led to NASA's Earth system science approach was *Earth System Science, A Program for Global Change*, report of the Earth System Sciences Committee, NASA, Washington, D.C., 1988.

<sup>3</sup>National Weather Service statistics presented in National Research Council, *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations*, The National Academies Press, Washington, D.C., pp. 24-25, 2003.

<sup>4</sup>L. Uccellini, NOAA National Centers for Environmental Prediction Advisory Panel meeting, January 12, 2005.

### BOX 1.1 IMPROVEMENTS IN WEATHER FORECASTING RESULTING FROM SATELLITE OBSERVATIONS

One of the greatest societal benefits provided by Earth sciences in the past 30 years has been the steady improvement of weather forecasts. Figure 1.1.1 shows the monthly moving average of the correlation (a perfect forecast is 100 percent) between observed and forecast weather features for 3-day, 5-day, and 7-day forecasts. The accuracy of forecasts of large-scale weather patterns in both hemispheres has been increasing steadily since 1980. The Southern Hemisphere forecast (bottom curve), which in 1980 was significantly worse than the Northern Hemisphere forecast (top curve), has caught up in accuracy in recent years. This dramatic improvement has been due largely to more and better global satellite data.

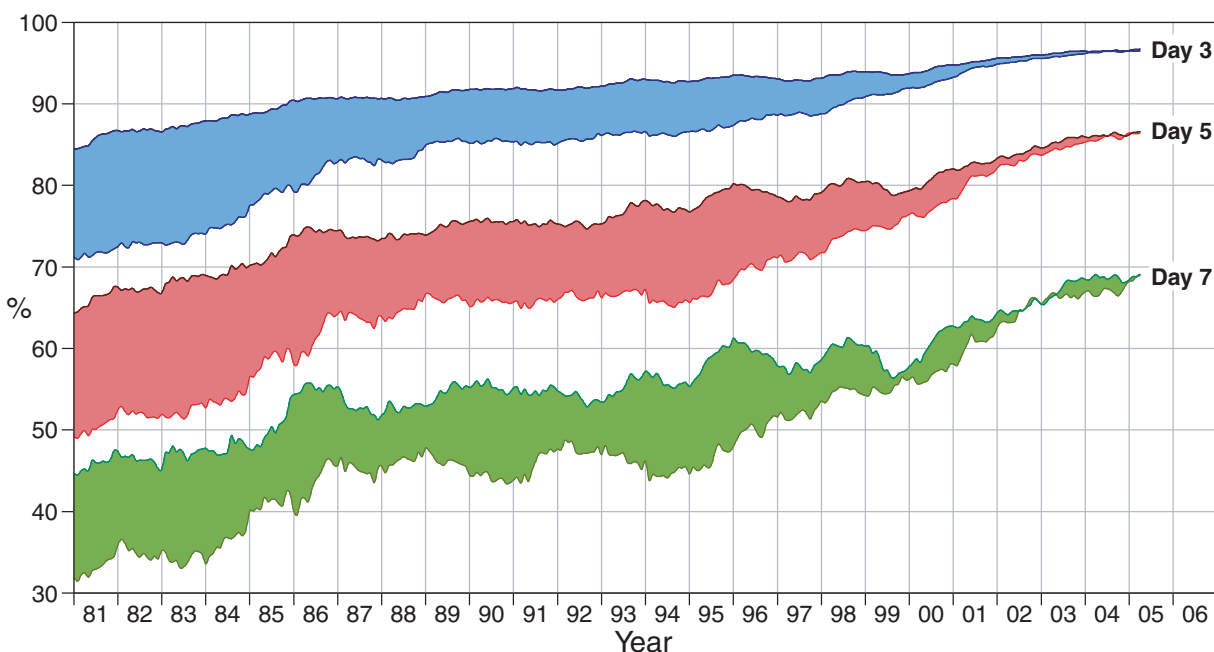


FIGURE 1.1.1 Anomaly correlation of 500 hPa height forecasts. SOURCE: Adapted from A.J. Simmons and A. Hollingsworth, 2002, "Some Aspects of the Improvement in Skill of Numerical Weather Prediction," *Q.J.R. Meteorol. Soc.* 128: 647-678. Copyright Royal Meteorological Society. Reprinted with permission.

that similar improvements are possible in seasonal climate forecasts, which are needed for a variety of agriculture decisions.<sup>5</sup>

<sup>5</sup>The 1997-1998 El Niño created torrential rains in California and led to rapid increases in food costs. See Kenneth Howe, "El Niño's Costly Crops," *San Francisco Chronicle*, February 26, 1998. Changes in sea temperature and sea surface topography observed by satellites and ocean moorings are critical for forecasting the strength and timing of impending El Niño events. Improved forecasts of the 1997-1998 El Niño event are estimated to have saved California residents on the order of \$1 billion compared to the costs of a similar event in 1982-1983, which was not forecast. See "The Economic Impacts of an El Niño," *Space Daily*, March 18, 2002, at <<http://www.spacedaily.com/news/pacific-02g.html>>.

Although weather and seasonal climate forecasts are a prominent example, Earth science knowledge has many other important applications. Today, we can track vast clouds of dust and pollution from their source on continents across the oceans, permitting health alarms to be sounded effectively. We can map deformations of Earth's surface and evacuate regions that may soon experience volcanic eruptions or landslides. We can track changes in soil moisture and then redirect food supplies to areas that may soon face drought and famine. We can monitor long-term changes in the land surface, atmosphere, and oceans and thereby characterize the impacts of human activities on climate. We have documented ozone loss in the stratosphere, resulting in the Montreal Protocol and termination of the production of the causative chlorofluorocarbons (CFCs). As these examples show, Earth information is essential to ensuring the prosperity and security of society as a whole.

Yet the more we apply this knowledge and observe its benefits, the more we identify new needs for basic knowledge, Earth information, credible forecasts, and decision-support structures designed to serve society. Businesses and national infrastructure elements, from transportation to energy, have a critical need for improved weather information.<sup>6</sup> Governments have obligations to manage new environmental treaties and regulations. Much of the U.S. and world population lives in areas that are subject to natural disasters, including hurricanes, tornadoes, floods, earthquakes, and tsunamis. Better forecasts are essential to protect lives and property from such disasters. Improved satellite observations of disaster areas can also speed relief and rebuilding efforts (Box 1.2).<sup>7</sup> Finally, effective management of natural resources—from clean water to oil and gas reserves to plants and animals—depends critically on the availability of better information and tools.

Despite many successes in applying Earth science information to improve lives, security, and the economy, we have the ability to do much more. The increase in knowledge produced over the last decade by Earth scientists is itself a tremendous societal benefit with clear public policy implications (Box 1.3). And the experience in applying that knowledge lays a solid foundation for more systematically selecting new missions that address not only important scientific issues but also critical societal needs.

*A fundamental challenge for the coming decade is to ensure that established societal needs help guide scientific priorities more effectively, and that emerging scientific knowledge is actively applied to obtain societal benefits.* New observations, analyses, better interpretive understanding, enhanced predictive models, broadened community participation, and improved means for information dissemination are all needed. If we meet this challenge, we will begin to realize the full economic and security benefits of Earth science.

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<sup>6</sup>It is estimated that 30 percent of the U.S. economy is sensitive to weather and climate. See Bureau of Economic Analysis figures reported in National Research Council, *The Atmospheric Sciences Entering the Twenty-First Century*, National Academy Press, Washington, D.C., p. 25, 1998. A weather forecast indicating a one-degree improvement in temperature is estimated to save companies generating electricity about \$35 million per year. See R.A. Williamson, H.R. Hertzfeld, and A. Sen, *Future Directions in Satellite-Derived Weather and Climate Information for the Electric Energy Industry: A Workshop Report*, Space Policy Institute, George Washington University, June 2004, at <<http://www2.gwu.edu/~spi/energy.pdf>>.

<sup>7</sup>For example, warning times for tornadoes have increased by 8 minutes since 1978. See National Weather Service statistics presented in National Research Council, *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations*, The National Academies Press, Washington, D.C., pp. 24–25, 2003. In addition, volcanic eruptions, landslides, and tsunamis can be predicted with increasing confidence in areas that are instrumented adequately. For example, scientists predicted the 1991 Mt. Pinatubo eruption, based on the increase in seismicity and surface deformation caused by the motion of magma within the volcano, enabling civil leaders to evacuate surrounding areas in time. See C. Newhall, J.W. Handley II, and P.H. Stauffer, "Benefits of Volcano Monitoring Far Outweigh Costs: The Case of Mount Pinatubo," *U.S. Geological Survey Fact Sheet* 115-97, 1997.



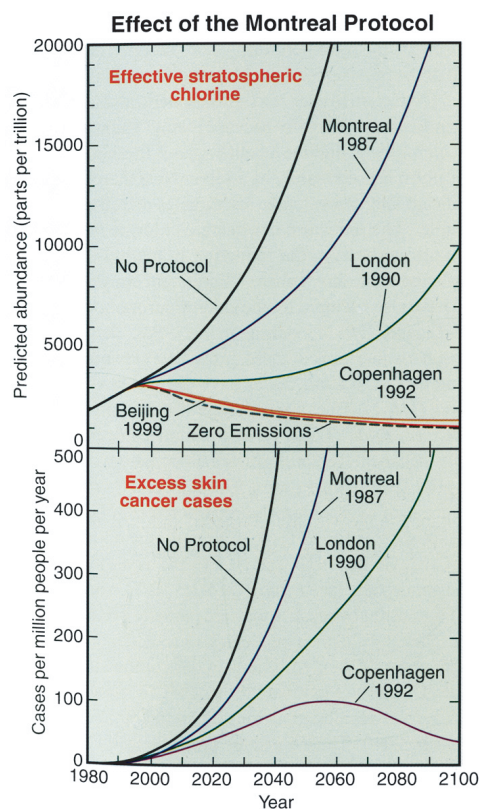
### BOX 1.2 THE TSUNAMI OF DECEMBER 26, 2004

The tragic events following the earthquake and tsunami in South Asia highlight the global need for coordinated disaster preparedness and response. Seismometers detected the earthquake that triggered the tsunami, and satellite altimeters detected the tsunami before it struck land (Plate 1). A tsunami warning system could potentially have saved tens of thousands of lives, but it did not exist in this region. In the aftermath of the disaster, a wide array of high-resolution satellite images and measurements are helping guide and monitor relief and recovery efforts and assisting in the deployment of resources (food, water, and medical supplies). As nations rebuild their devastated communities, Earth observations will provide critical inputs into decisions on the location, land use, and type of disaster-resistant construction practices that will improve human conditions in these disaster-prone regions. See, for example, the USGS National Map Hazards Data Distribution System at <[http://gisdata.usgs.gov/Website/Disaster\\_Response/viewer.php?Box=30.0:-30.0:120.0:45.0](http://gisdata.usgs.gov/Website/Disaster_Response/viewer.php?Box=30.0:-30.0:120.0:45.0)> and the Cornell University Tsunami reconnaissance relief site for Sri Lanka at <<http://polarbear.css.cornell.edu/srilanka/>>.

### BOX 1.3 HUMAN HEALTH, EXPOSURE TO ULTRAVIOLET RADIATION, AND OZONE

The Earth science and medical science communities have joined forces to understand and predict human morbidity rates resulting from the increasing incidence of skin cancer. Exposure to ultraviolet radiation, which damages DNA, is a risk factor for this cancer. Using satellite and other observations (Plate 2), Earth scientists have learned how the industrial release of CFCs leads to the dramatic loss of ozone over both the Arctic and the Antarctic. Their studies led to the regulation of an array of synthetic organic chlorine and bromine compounds through the Montreal Protocol and the ensuing London and Copenhagen amendments. A reduction of these compounds is projected to decrease the incidence of skin cancer, other factors being equal (Figure 1.3.1).

FIGURE 1.3.1 Effect of the Montreal Protocol. SOURCE: World Meteorological Organization, *Scientific Assessment of Ozone Depletion: 2002*, Global Ozone Research and Monitoring Project, WMO Report 47, 498 pp., Geneva, 2003.



## 2

# Earth Observations and Presidential Initiatives

*One of my main concerns . . . is ensuring that the full range of science, including Earth Science, remains a priority at NASA even as we move ahead to return to the moon by 2020. There simply is no planet more important to human beings than our own, and we're remarkably ignorant about it. NASA's Earth Science mission is essential.*

—House Science Committee Chairman Sherwood Boehlert  
speaking to the Consortium for Oceanographic Research and Education  
on March 9, 2005<sup>1</sup>

Three presidential initiatives concern Earth science and applications. Two of the initiatives—the 2001 U.S. Climate Change Research initiative<sup>2</sup> and the 2003 Global Earth Observation initiative<sup>3</sup>—underscore both the traditional U.S. value of pushing back the frontiers of knowledge and the practical importance of obtaining Earth science information to meet national and international objectives. They directly support the need to protect life and property through improved forecasting and to promote economic vitality, while increasing knowledge and understanding about the complex planet on which we live. A third presidential initiative, the 2004 Vision for Space Exploration, looks beyond Earth and establishes new priorities for NASA.<sup>4</sup>

The Climate Change Research initiative led to the establishment of the national Climate Change Science Program (CCSP).<sup>5</sup> The CCSP encompasses the programs of the U.S. Global Change Research

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<sup>1</sup>The full text of Rep. Boehlert's speech is available at <<http://www.house.gov/science/press/109/109-33.htm>>.

<sup>2</sup>See <<http://www.climatevision.gov/statements.html>>.

<sup>3</sup>See <<http://www.whitehouse.gov/news/releases/2002/02/20020214-5.html>> and <[http://www.earthobservationsummit.gov/press\\_release\\_whfs.html](http://www.earthobservationsummit.gov/press_release_whfs.html)>.

<sup>4</sup>See <<http://www.whitehouse.gov/news/releases/2004/01/20040114-1.html>>.

<sup>5</sup>Thirteen federal agencies participate in the program, which is managed by a subcommittee chaired by James Mahoney, NOAA.



Program, which was itself a presidential initiative of a previous administration. In addition to advancing understanding of the climate system, the CCSP has established three goals to improve the ability to predict and cope with the effects of climate change: (1) reduce uncertainty in projections of how Earth's climate and related systems may change in the future; (2) understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes; and (3) explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.<sup>6</sup>

The Global Earth Observation initiative led to the Earth Observation Summit, hosted by the United States, in July 2003 in Washington, D.C. Thirty-three nations and the European Commission participated in the summit and affirmed "the need for timely, quality, long-term, global information as a basis for sound decision making."<sup>7</sup> They noted, "In order to monitor continuously the state of the Earth, to increase understanding of dynamic Earth processes, to enhance prediction of the Earth system, and to further implement our environmental treaty obligations, we recognize the need to support improved coordination of strategies and systems for observations of the Earth and identification of measures to minimize data gaps, with a view to moving toward a comprehensive, coordinated, and sustained Earth observation system or systems. . . ." At the second Earth Observation Summit, held in Tokyo in April 2004, the concept of the Global Earth Observing System of Systems (GEOSS) was accepted. Participating governments accepted the draft 10-year plan to implement GEOSS at the third summit, held in Brussels in February 2005.

Finally, the president's vision for space exploration initiative<sup>8</sup> led to a reorganization of NASA and established a new focus on exploration of the Moon, Mars, and solar system. The planning document that accompanied NASA's FY 2006 budget proposal lists five guiding national objectives for NASA, including "study the Earth system from space and develop new space-based and related capabilities for this purpose."<sup>9</sup> However, the priority for Earth observations, which have direct and immediate relevance to society, appears greatly diminished in terms of the projected declining budgets that are proposed for FY 2006. *The committee strongly believes that NASA must retain Earth science as a central priority, to support critical improvements in understanding our planet and developing useful applications.*

Prior to setting a decadal agenda, which is the task of the Committee on Earth Science and Applications from Space and its panels during the next year, it is important to recognize emerging threats to the execution of Earth science research and applications programs. The reallocation of resources within NASA has emerged as a dominant consideration in addressing the decadal agenda. Resources available to Earth observation programs are declining, making it difficult for NASA to fulfill its obligations to the CCSP and GEOSS. A comparison of NASA's proposed FY 2006 budget with previous budgets indicates that plans for at least six Earth observing missions have been canceled, descoped, or delayed. Explorer-class missions—conducted under NASA's Earth System Science Pathfinder program and intended to provide a continuous

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<sup>6</sup>The other CCSP goals are to (1) improve knowledge of Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change and (2) improve quantification of the forces bringing about changes in Earth's climate and related systems. See Climate Change Science Program and Subcommittee on Global Change Research, *Strategic Plan for the U.S. Climate Change Science Program*, Washington, D.C., 202 pp., 2003.

<sup>7</sup>See <<http://earthobservations.org/default.asp>>. The summit also affirmed the need for (1) a coordinated effort to involve and assist developing countries in improving and sustaining their contributions to observing systems, (2) the timely exchange of observations, and (3) a process for the preparing a 10-year implementation plan. To this end, the summit established the ad hoc Group on Earth Observations.

<sup>8</sup>*A Renewed Spirit of Discovery, the President's Vision for U.S. Space Exploration*, The White House, January 2004.

<sup>9</sup>National Aeronautics and Space Administration, *The New Age of Exploration: NASA's Direction for 2005 and Beyond*, NP-2005-01-397-HQ, Washington, D.C., 2005, <[http://www.nasa.gov/pdf/107490main\\_FY06\\_Direction.pdf](http://www.nasa.gov/pdf/107490main_FY06_Direction.pdf)>.

infusion of new technology and ideas into Earth science programs and to build human capacity for future scientific and technological advances—have been repeatedly delayed.

In addition, the committee is concerned that significant resources for the research and analysis (R&A)<sup>10</sup> programs that sustain the interpretation of Earth science data have been reallocated either as a result of the removal of the “firewall” that previously existed between flight and science programs or as an unintended consequence of NASA’s shift to full-cost accounting. Because the R&A programs are carried out largely through the nation’s universities, there will be an immediate and deleterious impact on graduate student, postdoctoral, and faculty research support. The long-term consequence will be a diminished ability to attract and retain students interested in using and developing Earth observations. Taken together, these developments jeopardize U.S. leadership in both Earth science and Earth observations, and they undermine the vitality of the government-university-private sector partnership that has made so many contributions to society.

In Chapter 3 the committee makes a number of recommendations to restore the health of the Earth observations and related research and operational effort in the United States and to set the stage for steady advances in Earth science and applications over the next decade.

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<sup>10</sup>R&A has customarily supplied funds for enhancing fundamental understanding in a discipline and stimulating the questions from which new scientific investigations flow. R&A studies also enable conversion of raw instrument data into fields of geophysical variables and are an essential component in support of the research required to convert data analyses to trends, processes, and improvements in simulation models. They are likewise necessary for improving calibrations and evaluating the limits of both remote and in situ data. Without adequate R&A, the large and complex task of acquiring, processing, and archiving geophysical data would go for naught. Finally, the next generation of Earth scientists—the graduate students in universities—are often educated by performing research that has originated in R&A efforts. See National Research Council, *Earth Observations from Space: History, Promise, and Reality (Executive Summary)*, National Academy Press, Washington, D.C., 26 pp., 1995.

## 3

# Critical Needs for Today

U.S. satellite observing systems are undergoing a major transition. NASA's Earth Observing System (EOS) has been launched and is producing an extraordinary array of science, yet almost no new research missions are planned or are in development. The National Polar-orbiting Operational Environmental Satellite System (NPOESS), scheduled for launch in late 2009, will replace polar-orbiting weather satellites flown separately by NOAA and the Department of Defense. It will be preceded by a transitional and risk-reduction mission to be launched in late 2006, the NPOESS Preparatory Program (NPP). And beginning in 2012, NOAA's Geostationary Operational Environmental Satellite (GOES) will be upgraded to improve weather forecasts, hazard monitoring, and atmospheric research.

The decisions behind these transition plans, many of them made during the 1990s, both create and limit the opportunities that are available over the next decade and beyond. For example, the decision to integrate climate observations into NPOESS creates some efficiencies. But it also introduces significant compromises in instrument and information system capabilities and limitations in the resulting value of the observations for climate applications.

The U.S. government's historic approach of dividing responsibility for Earth observations also constrains what new missions can be flown. Under the current arrangement, NASA is responsible for research missions, NOAA is responsible for operational missions, and the USGS has certain responsibilities for the Landsat missions and for land-based monitoring systems. However, as research and operational applications become more tightly integrated, it will be necessary to reconsider how to manage these functions and accelerate the rate of transition of research results to operational products of use to society.<sup>1</sup>

The ability to capitalize on previous research for both new science and societal applications requires a robust scientific and technological program aimed at making systematic progress in understanding Earth as a system and creating new knowledge and applications. This interim report focuses on actions required

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<sup>1</sup>National Research Council, *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations*, The National Academies Press, Washington, D.C., 2003.

within the next year; it is based on the committee’s review and analysis of mission plans that were current as of April 2005. The committee did not attempt to evaluate new missions—a task whose results will be presented in the committee’s final report in late 2006.

As a result of recent mission cancellations, budget-induced delays, and mission descopes, the committee finds the existing Earth observing program to be severely deficient. The near-term recommendations presented below describe the minimum set of actions needed to maintain the health of the NASA scientific and technical programs until more comprehensive community recommendations are made in the committee’s final report. They address deficiencies in the current program at NASA and some of the emerging needs of NOAA and the USGS. The recommendations address issues in six interrelated areas:

1. Canceled, descoped, or delayed Earth observation missions;
2. Prospects for the transfer of capabilities from some canceled or descoped NASA missions to NPOESS;
3. The adequacy of the technological base for future missions;
4. The status and future prospects of NASA Earth science Explorer-class missions;
5. The adequacy of research and analysis programs to support future programs; and
6. Development of baseline climate observations and data records.

Table 3.1 summarizes a number of recent Earth observing missions or mission programs that have been canceled, descoped, or delayed. The instruments on all of these missions have been demonstrated technologically and are ready for near-term launch. All have important societal applications, as discussed below.

TABLE 3.1 Canceled, Descoped, or Delayed Earth Observation Missions

Mission	Measurement	Societal Benefit	Status
Global Precipitation Measurement (GPM)	Precipitation	Reduced vulnerability to floods and droughts; improved capability to manage water resources in arid regions; improved forecasts of hurricanes	Delayed
Atmospheric Soundings from Geostationary Orbit (GIFTS—Geostationary Imaging Fourier Transform Spectrometer)	Temperature and water vapor	Protection of life and property through improved weather forecasts and severe storm warnings	Canceled
Ocean Vector Winds (active scatterometer follow-on to QuikSCAT)	Wind speed and direction near the ocean surface	Improved severe weather warnings to ships at sea; improved crop planning and yields through better predictions of El Niño	Canceled
Landsat Data Continuity—bridge mission (to fill gap between Landsat-7 and NPOESS)	Land cover	Monitoring of deforestation; identification of mineral resources; tracking of the conversion of agricultural land to other uses	Canceled
Glory	Optical properties of aerosols; solar irradiance	Improved scientific understanding of factors that force climate change	Canceled
Wide Swath Ocean Altimeter (on the Ocean Surface Topography Mission; OSTM)	Sea level in two dimensions	Monitoring of coastal currents, eddies, and tides, all of which affect fisheries, navigation, and ocean climate	Instrument canceled—descoped of an enhanced OSTM

The committee's conclusions and recommendations regarding these missions are presented in the sections that follow.

## PROCEED WITH GPM AND GIFTS

### Global Precipitation Measurement

In spite of steady advances in weather predictions and warnings, society is increasingly vulnerable to costly floods and droughts.<sup>2</sup> Accurate measurement and prediction of precipitation are essential to reduce this vulnerability and improve the management of water resources. Such measurements can be obtained from spaceborne active microwave sensing (radar), which provides direct, fine-scale observations of the three-dimensional structure of precipitation systems.

The first spaceborne precipitation radar, on the Tropical Rainfall Measuring Mission (TRMM), was launched in 1997 and provided insights into the microphysical dynamics of the formation of precipitation. These measurements led to improved operational forecasts of precipitation and estimates of hurricane storm tracks, which in turn have almost certainly reduced economic losses and saved lives.<sup>3</sup> TRMM has already exceeded its planned lifespan, and a replacement, the Global Precipitation Measurement (GPM) mission, will be built in partnership with Japan, Europe, and possibly France and India. GPM will consist of a core satellite with a precipitation radar and an advanced radiometer, accompanied by approximately seven satellites with passive radiometers. The GPM constellation will provide global coverage at 3-hour intervals over most land and ocean areas (latitude 65° S to 65° N).

GPM was originally planned to be launched in 2007, which would have minimized the gap in global precipitation coverage after TRMM ended. However, the current estimated launch date is 2010. The committee is pleased to see that GPM is in NASA's proposed FY 2006 budget but is concerned that the planned launch date has slipped 3 years since initial planning.

**The committee recommends that the Global Precipitation Measurement mission be launched without further delays.**

### Atmospheric Soundings from Geostationary Orbit

Atmospheric soundings of temperature and water vapor are routinely made from polar-orbiting satellites, and they contribute essential observations for weather forecasting. However, the time between soundings from a single polar-orbiting satellite is approximately 12 hours, and this sampling frequency is too low for observing the development of and the rapid changes associated with severe weather, including tornadoes, flash floods, and hurricanes. High-frequency soundings over the United States are being made from geostationary orbit, and there is a plan to upgrade these and other capabilities in 2012 with the launch of the next-generation operational GOES sounder, GOES-R. The Geostationary Imaging Fourier Transform Spectrometer (GIFTS) is a new technology that is designed to obtain 80,000 closely spaced

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<sup>2</sup>For instance, the 1988 central U.S. drought is estimated to have cost \$40 billion to \$60 billion. See information compiled by NOAA's National Climatic Data Center at <http://www.ncdc.noaa.gov/oa/reports/billionz.html>. Global flood losses over the last decade have exceeded \$200 billion, according to the Munich Reinsurance Company, *World Map of Natural Hazards*, Munich, Germany, 1998.

<sup>3</sup>Although TRMM data contribute to El Niño predictions, the socioeconomic effects of TRMM-improved forecasts have not yet been quantified. See National Research Council, *Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission: A Perspective from the Research and Operations Communities*, Interim Report, The National Academies Press, Washington, D.C., 2005, in press.

horizontal (~4-kilometer), high-vertical-resolution (~1-kilometer) atmospheric temperature and water vapor soundings every minute from geostationary orbit.<sup>4</sup> The high-vertical-resolution water vapor flux measurements also provide a measure of the winds. These measurements will significantly improve numerical weather prediction and severe weather warnings.

The components of GIFTS have been developed with more than \$100 million of prior NASA support<sup>5</sup> and are being assembled as a prototype for GOES-R risk reduction. However, facing budget problems that were partly the result of the Navy's withdrawal of its planned support for a spacecraft and launch vehicle, NASA discontinued funding for the GIFTS project beyond FY 2005. The result was a shortfall in funds needed to complete the fabrication and testing of the GIFTS instrument. NOAA provided additional financial support to complete integration of the components of GIFTS and carry out thermal vacuum tests, which will be completed later in 2005. But no funds have been identified to finish the space qualification of GIFTS, and a space mission opportunity has not yet been secured. A World Meteorological Organization (WMO)-led international effort (International Geostationary Laboratory, IGeoLab)<sup>6</sup> is getting underway to test GIFTS in space. The plan is to position GIFTS over different regions of Earth to demonstrate the global value of the observations and to prepare the international community for the use of similar data from future operational geostationary satellites. This test could occur as early as 2008, providing 4 years of useful data before the launch of GOES-R.

**The committee recommends that NASA and NOAA complete the fabrication, testing, and space qualification of the GIFTS instrument and that they support the international effort to launch GIFTS by 2008.**

#### EVALUATE PLANS FOR TRANSFERRING NEEDED CAPABILITIES TO NPOESS

Instruments on three canceled missions may either be transferred from NASA or replaced with other instruments for flight on NPOESS. These instruments would provide a capability to measure ocean vector winds, land surface changes, aerosol properties, and solar irradiance. Transferring these capabilities from independent NASA missions to NPOESS brings advantages (e.g., transfer of research capabilities to operational use) and disadvantages (e.g., decreased instrument capability, data gaps), as discussed below.

#### Ocean Vector Winds

Measurements of wind speed and direction near the ocean surface (ocean winds) by satellite observation systems are crucial for monitoring the motion of the atmosphere and oceans and their interaction.<sup>7</sup> In particular, accurate knowledge of ocean winds is vital to studies of air-sea interactions,<sup>8</sup> ocean circula-

<sup>4</sup>See <[http://cimss.ssec.wisc.edu/itwg/itsc/itsc13/proceedings/session7/7\\_1\\_1emarshall.pdf](http://cimss.ssec.wisc.edu/itwg/itsc/itsc13/proceedings/session7/7_1_1emarshall.pdf)>.

<sup>5</sup>Personal communication, R. Reisse, NASA GIFTS project manager, March 8, 2005.

<sup>6</sup>See <[http://www.eumetsat.int/en/area2/cgms/cgms\\_xxxii/CGMS-XXXII\\_Working\\_Papers/CGMS-XXXII\\_EUM\\_WPs/CGMS-XXXII\\_EUM\\_WP\\_18.pdf](http://www.eumetsat.int/en/area2/cgms/cgms_xxxii/CGMS-XXXII_Working_Papers/CGMS-XXXII_EUM_WPs/CGMS-XXXII_EUM_WP_18.pdf)>.

<sup>7</sup>Although instruments on buoys and ships provide measurements of surface wind vectors, their coverage is insufficient to provide a global wind map. In contrast, satellite-based sensors can provide near-global coverage in one day. Moreover, QuikSCAT ocean winds have proven to be highly accurate. See M.H. Freilich and R.S. Dunbar, "The Accuracy of the NSCAT 1 Vector Winds: Comparisons with National Data Buoy Center Buoys," *J. Geophys. Res.* 104(C5): 11231, 1999.

<sup>8</sup>For example, ocean wind data will support an NSF-sponsored field program (Clivar Mode Water Dynamics Experiment) to study the details of air-sea interaction and improve climate models.



tions, and El Niño forecasts.<sup>9</sup> Accurate ocean winds also improve weather forecasts and storm warnings. The use of QuikSCAT wind data, for example, improved National Weather Service forecasts of the four hurricanes that devastated the southeast United States in 2004 and marine warnings to ships at sea.<sup>10</sup> Furthermore, by improving the ability to anticipate how climate and weather will change from one season or year to the next, ocean winds can help us to better manage global agriculture, water reserves, and other resources.

Microwave scatterometers have been flown by NASA and the European Space Agency since 1991, and ocean wind data have been assimilated into weather forecast systems for several years. The current scatterometer—SeaWinds—was launched in 1999 on NASA's QuikSCAT satellite as a "quick recovery" mission intended to fill the data gap when the satellite hosting the NASA Scatterometer (NSCAT) lost power in June 1997. QuikSCAT has already exceeded its planned 3-year lifetime, but the follow-on NASA mission (Ocean Vector Winds mission), originally scheduled for launch in 2008, has been canceled by NASA.

Both active (radar) and passive (radiometer) microwave sensors are capable of determining ocean surface wind speed, and active microwave instruments are also used to derive the wind direction. The European Space Agency plans to launch an active scatterometer instrument (the Advanced Scatterometer, ASCAT) on its MetOp-1 satellite in late 2005.<sup>11</sup> However, it has only about half of the coverage of QuikSCAT (two narrower bands with a gap in the middle). Moreover, significant improvements to weather forecasts require more than one instrument because of the large space between swaths.<sup>12</sup>

A passive microwave sensor (Windsat<sup>13</sup>) has been launched to test the technology for the Conical Scanning Microwave Imager/Sounder (CMIS) instrument, which will be launched on the first NPOESS.<sup>14</sup> Preliminary analysis suggests that such passive systems will produce wind observations with less accuracy and with more contamination by rain and land than active scatterometers.<sup>15</sup> As a result, the substitution of passive microwave sensor data for scatterometry data would worsen El Niño and hurricane forecasts and weather forecasts in coastal areas.<sup>16</sup>

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<sup>9</sup>In an El Niño year, changes in wind and ocean circulation alter typical rainfall patterns and result in the release of large amounts of heat into the atmosphere. The subsequent energy propagates within the atmosphere, affecting the weather in various ways and places and disrupting the normal rhythm of life across the Pacific Ocean. The ability to accurately predict El Niño is of great benefit to the United States and to countries around the world.

<sup>10</sup>NASA/NOAA workshop, "Satellite Measurements of Ocean Vector Winds: Present Capabilities and Future Trends," Florida International University, Miami, Florida, February 8-10, 2005. See presentations at <[http://cioss.coas.oregonstate.edu/CIOSS/workshops/miami\\_meeting/Agenda.html](http://cioss.coas.oregonstate.edu/CIOSS/workshops/miami_meeting/Agenda.html)>. A forecaster from the National Centers for Environmental Prediction's Tropical Prediction Center stated that "without QuikSCAT they would be forecasting in the dark."

<sup>11</sup>See <<http://www.esa.int/export/esaME/ascats.html>>.

<sup>12</sup>R. Knabb, C. Hennon, D. Brown, J. Franklin, H. Cobb, J. Rhone, and R. Molleta, "Impact of QuikSCAT on Tropical Prediction Center Operations," presentation at NASA/NOAA workshop, Florida International University, Miami, Fla., February 8-10, 2005; see presentation at <[http://cioss.coas.oregonstate.edu/CIOSS/workshops/miami\\_meeting/Agenda.html](http://cioss.coas.oregonstate.edu/CIOSS/workshops/miami_meeting/Agenda.html)>.

<sup>13</sup>Unfortunately, shortly before this report was completed (early May 2005), Windsat suffered a mission-threatening on-orbit failure.

<sup>14</sup>Windsat was built by the Naval Research Laboratory, with cooperation from NASA, the Air Force, and the NPOESS Integrated Program Office.

<sup>15</sup>M.H. Freilich and B.A. Vanhoff, "The Accuracy of Preliminary Windsat Vector Wind Measurements: Comparisons with NDBC Buoys and QuikSCAT," *IEEE Trans. Geosci. Remote Sensing*, 2006, in press.

<sup>16</sup>The passive system does not provide useful wind direction for winds of 5 meters per second or less (scatterometer threshold is 2 meters per second). Moreover, wind direction errors for winds at 6 to 8 meters per second (the wind speed range that forces ENSO events) will be double that of the scatterometer. The median global wind speed is about 7 meters per second, which suggests that a passive system will not provide reliable information on direction for half of the winds. In addition, rain and land contamination of wind vectors will be greater from a passive system than from a scatterometer, which limits their use in forecasts of hurricanes and weather in coastal regions. Windsat is comparable in quality to QuikSCAT for wind speeds greater than 8 meters per second, in the absence of rain. However, forecasters at a recent workshop noted that even the relatively small dropout rate of QuikSCAT data from rain was a concern. See presentations at a NASA/NOAA workshop, "Satellite Measurements of Ocean Vector Winds: Present Capabilities and Future Trends," Florida International University, Miami, Fla., February 8-10, 2005, at <[http://cioss.coas.oregonstate.edu/CIOSS/workshops/miami\\_meeting/Agenda.html](http://cioss.coas.oregonstate.edu/CIOSS/workshops/miami_meeting/Agenda.html)>.

### **Landsat Data Continuity**

Landsat has provided the longest and best-calibrated time series of information about changes in land cover and land use for over 30 years. Today, however, the continuity of this data record is at risk. Despite the varied ongoing uses of Landsat data, the program has not been put on a truly operational basis. The current mission—Landsat 7—is operating in a diminished capacity<sup>17</sup> and has exceeded its design life, and NASA has canceled the Landsat Data Continuity Mission.<sup>18</sup>

The plan outlined in the president's FY 2006 budget is to have NASA provide an Operational Land Imager (OLI) for flight on the first NPOESS platform. This decision increases the likelihood that critical land cover measurements will be sustained during the NPOESS era. However, since the scan line connector malfunctioned in 2003, Landsat 7 has not been able to achieve the goal of refreshing the global data set seasonally. Consequently, a significant data gap in the Landsat record is already occurring. Actions proposed in NASA's FY 2006 plan will further increase this data gap, and the gap will obviously be considerably longer if the NPOESS launch date is delayed.

The gap cannot be completely filled by land surface data collected by commercial and foreign sources. Each of these alternative sources has disadvantages, including the high cost of purchasing data or reprogramming algorithms to analyze the data, lack of calibration, and limited geographic coverage. Moreover, the proposed use of the large NPOESS platform to acquire Landsat-type imagery raises technical concerns, including the demands of the imager on the volume and throughput of data systems, and the influence of the jitter of a large platform on the image quality.

### **Aerosols and Total Irradiance Monitor—Glory**

The Glory mission,<sup>19</sup> which was to fly the Advanced Polarimetric Sensor (APS) to measure optical properties of aerosols and the Total Irradiance Monitor (TIM) to measure solar irradiance, is slated for cancellation. The Glory mission would provide data essential for climate research and prediction—it would yield the first global aerosol measurements with composition specificity and precise microphysical data on both aerosols and cloud particles needed to infer direct and indirect aerosol climate forcings. It also would ensure continuity of the solar irradiance time series, which goes back to 1978 and whose value would be diminished should there be any gap in the measurement.<sup>20</sup>

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<sup>17</sup>In June 2003 a failure of the scan line corrector (SLC) diminished the capability of the ETM+ (Enhanced Thematic Mapper, plus) instrument. For a description of the problem, see <http://landsat.usgs.gov/pdf/2003junelmu.pdf>. Without the SLC, the sensor still provides coverage of approximately 78 percent of each scene. However, the temporal repeat frequency of coverage has been severely affected and now takes two or more acquisitions to produce one complete view.

<sup>18</sup>NASA and the Department of the Interior/USGS initially planned to avoid a data gap after Landsat 7 by implementing a Landsat Data Continuity Mission (LDCM) that would procure data from a privately owned and commercially operated remote sensing system. Following an evaluation of proposals, NASA declined to accept any offers and canceled this plan in September 2003. A memorandum from the Office of Science and Technology Policy (OSTP), signed on August 13, 2004, by OSTP Director John Marburger III, states that "the Departments of Defense, the Interior, and Commerce and the National Aeronautics and Space Administration have agreed to take the following actions: (1) Transition Landsat measurements to an operational environment through the incorporation of Landsat-type sensors on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) platform; (2) Plan to incorporate a Landsat imager on the first NPOESS spacecraft (known as C-1), currently scheduled for launch in late 2009; (3) Further assess options to mitigate the risks to data continuity prior to the first NPOESS-Landsat mission, including a 'bridge' mission." The bridge mission is no longer an option in the President's FY 2006 budget. The OSTP memorandum can be found at the NASA LDCM Web site at <http://ldcm.nasa.gov>.

<sup>19</sup>See [http://www.esa.ssc.nasa.gov/m2m/mission\\_report.aspx?mission\\_id=233](http://www.esa.ssc.nasa.gov/m2m/mission_report.aspx?mission_id=233).



The cancellation of the Glory mission is especially worrisome because just last year, at the January 2004 meeting of the American Meteorological Society, NASA Administrator Sean O'Keefe called for accelerating the flight of the Glory mission to meet NASA's commitment to the CCSP.<sup>21</sup> To go from acceleration to cancellation in 1 year may reflect programmatic and other difficulties for Earth sciences at NASA in general. However, the cancellation has also had impacts on the NPOESS program.

The APS had originally been scheduled to fly on NPOESS in 2010, but when NASA chose its own procurement path for the APS instrument on Glory, the Integrated Program Office for NPOESS significantly delayed its procurement plans for APS. As a consequence, if the APS procurement is reinstated in NOAA plans, the instrument will not be available to fly until 2012 at the earliest. However, the APS and TIM instruments can fly on the first NPOESS mission if NASA builds them and pays for their integration costs.

This record of start then stop, of acceleration then delay, and of canceling important missions without notice is at odds with NASA's stated science goals and commitment to the CCSP. Moreover, decisions to transfer capabilities from NASA to NOAA were not always made after an appropriate study of the advantages and disadvantages of an NPOESS solution, or with adequate consultation with the scientific and user community. The committee recognizes that there are substantial competing demands on NASA's budget and that additional funds will be needed to fully address the recommendations in this report.

**The committee recommends that NASA, NOAA, and the USGS commission three independent reviews, to be completed by October 2005, regarding the Ocean Vector Winds, Landsat Data Continuity, and Glory missions.<sup>22</sup> The reviews should evaluate:**

- **The suitability, capability, and timeliness of the OLI and CMIS instruments to meet the research and operational needs of users, particularly those that have relied on data from Landsat and QuikSCAT;**
- **The suitability, capability, and timeliness of the APS and TIM instruments for meeting the needs of the scientific and operational communities;**
- **The costs and benefits of launching the Landsat Data Continuity and Glory missions prior to and/or independently of the launch of the first NPOESS platform; and**
- **The costs and benefits of launching the Ocean Vector Winds mission prior to or independently of the launch of CMIS on NPOESS.**

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<sup>20</sup>Six overlapping satellite experiments have monitored solar irradiance since late 1978: (1) NOAA's Nimbus-7 Earth Radiation Budget (ERB) experiment (1978-1993), (2) NASA's Active Cavity Radiometer Irradiance Monitor (ACRIM) 1 on the Solar Maximum Mission (1980-1989), (3) NASA's Earth Radiation Budget Experiment on the Earth Radiation Budget Satellite (ERBS) (3 missions, running from 1984 to today), (4) NASA's ACRIM2 on the Upper Atmosphere Research Satellite (1991-2001), and (5) NASA's ACRIM3 on the ACRIMSAT satellite (2000 to present). The European Space Agency's SOHO/VIRGO experiment also provided an independent data set during the period from 1996 to 1998.

<sup>21</sup>O'Keefe noted, "Nearly three years ago the President announced a significant Climate Change Research Initiative that now engages the talents of several federal agencies, including NASA. The Administration's decadal strategic plan for Climate Change Science calls for three major areas of emphasis to accelerate the availability of the scientific information and models needed to help inform policy decisions. The first area of emphasis is on the emerging science of non-CO<sub>2</sub> greenhouse gas forcing, especially aerosols; carbon over North America; and climate feedbacks involving clouds, water vapor, and Polar Regions. . . . As part of NASA's commitment to the Climate Change science program, we hope to accelerate the flight of the Glory mission to as early as 2007 to provide earlier availability of this space-based polarimeter that measures the optical properties of aerosols and clouds. This device is slated to become a regular part of the next generation military and civilian weather satellite system." Remarks given by Sean O'Keefe, American Meteorological Society, Seattle, Washington, on January 11, 2004. See <[http://www.nasa.gov/audience/formedia/speeches/ok\\_meteorological\\_society\\_011104.html](http://www.nasa.gov/audience/formedia/speeches/ok_meteorological_society_011104.html)>.

<sup>22</sup>Note added in proof: Wording corrected to include the USGS, which was inadvertently omitted in the prepublication copy of this report.

**If the benefits of an independent NASA mission(s) cannot be achieved within reasonable costs and risks, the committee recommends that NASA build the OLI (two copies, one for flight on the first NPOESS platform<sup>23</sup>), APS, and TIM instruments and contribute to the costs of integrating them into NPOESS. APS, TIM, and the first copy of OLI should be integrated onto the first NPOESS platform to minimize data gaps and achieve maximum utility.**

The reviews could be conducted under the auspices of NASA and NOAA and USGS external advisory committees or other independent advisory groups and should be carried out by representative scientific and operational users of the data, along with NOAA and NASA technical experts.

### **DEVELOP A TECHNOLOGY BASE FOR FUTURE EARTH OBSERVATION**

NASA's Earth Observing System was intended to serve as the foundation for its long-term efforts in Earth science and applications. EOS involves a number of instruments and platforms, a community of world-class scientists, and the infrastructure to consolidate data and information from surface campaigns and remote sensing satellites. The centerpiece of the system is a set of three spacecraft with multiple instruments for studying processes over land, oceans, and atmosphere—EOS Terra, Aqua, and Aura, respectively. Initial plans made in the 1980s called for development of three series of each of these satellites. With launches every 18 to 24 months and replacements every 5 years, NASA hoped to ensure at least a 15-year record of continuous measurements to address the highest-priority science and policy questions, as identified by the interagency Committee on Earth and Environmental Sciences and the Intergovernmental Panel on Climate Change (IPCC).

NASA has changed plans for the EOS series so that now there will be no follow-on spacecraft launched as the second or third elements of Terra, Aqua, or Aura. The development of the longer-term records rests now with the NPOESS, GOES-R, and foreign missions. Aside from selected (and delayed) ESSP missions, the Ocean Surface Topography mission (Jason-2), which no longer has the wide-swath altimeter option, and the Global Precipitation Measurement mission, the NASA program for the future has no explicit set of Earth observation mission plans. Moreover, there is no corresponding research and analysis program for NPOESS as there was for EOS.

Given the long lead times (up to a decade)<sup>24</sup> required to identify user needs and develop instrument capabilities, it is essential to have a prioritized science mission strategy based on compelling scientific issues and societal needs and opportunities. Beginning in 2005, the ESSP process will result in a new mission every 2 to 3 years; however, this process is completely inadequate to meet established needs of Earth science or society. Indeed, ESSP was initially conceived as a means to augment the existing EOS line with smaller, more rapid, and technologically flexible missions. Soon there will be little to augment, and the ESSP is, itself, stretched out and delayed.

The absence of a robust set of out-year science missions in active development and in a planning queue is troubling because a number of societally important and scientifically compelling mission con-

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<sup>23</sup>The LDCM option that is currently under consideration would procure two imaging instruments, each with a mission lifetime of 5 years, to be flown on NPOESS and provide continuity to the Landsat 7 data set.

<sup>24</sup>For large observational programs such as NPOESS, the time from concept to launch can take the better part of a decade. In contrast, some of the smaller, cheaper, and less complex Explorer-class programs can be executed in less than 4 years. A good example of this possibility of rapid execution is the recently awarded Interstellar Boundary Experiment (IBEX), which will be launched in 2008. As discussed in the text, ESSP missions were also designed to allow rapid execution; however, budget constraints have resulted in delays such as those seen in the Hydros mission, which was selected in 2002 but will not launch until September 2010 or later.

cepts are ready to be implemented. Further, the absence of out-year missions will likely result in a stagnant technology base.

The committee's final report will include a prioritized list of Earth observation missions and activities. This interim report does not preview those recommendations, but the committee can foresee needed technologies for missions that have been under discussion for several years. Three examples with great societal relevance are interferometric synthetic aperture radar, wide-swath ocean altimetry, and measurement of tropospheric winds from space.

Interferometric synthetic aperture radar (InSAR) has demonstrated the capability to make fundamental contributions to understanding the processes that cause earthquakes, volcanic eruptions, and landslides.<sup>25</sup> However, existing InSAR satellites, which are being flown by the Canadian and European space agencies, have serious limitations:

- The radars collect data in the C-band, which does not work well in vegetated areas; and
- Demand is so high that images are available only for limited areas and at limited times.

Even without these limitations, continued information from these satellites is problematic as they have reached the end of their useful lifetimes.

The shortage of InSAR images will also limit the success of EarthScope, a multi-agency program to explore the three-dimensional structure of the North American continent,<sup>26</sup> and efforts to monitor earthquake and volcano hazards around the world. For these reasons, an InSAR mission has emerged as the top priority for the solid-Earth community.<sup>27</sup> Investments in the technological base for the L-band are needed to move forward on this mission.

To map the sea-surface height in two dimensions with satisfactory resolution, a new type of radar instrument using the principle of radar interferometry has been developed at the Jet Propulsion Laboratory (JPL). JPL's wide-swath ocean altimeter has the potential to provide ocean topography over a 200-kilometer-wide swath, providing a two-dimensional image of sea-surface height, rather than a one-dimensional profile. The wide-swath ocean altimeter was being planned for flight on the international Ocean Surface Topography Mission (Jason-2) but was eliminated because of budgetary reasons. This exciting capability enables measurement of small-scale but important phenomena, such as vortices inside ocean currents, which are needed to improve ocean circulation models and to support marine transportation and fisheries research and forecasts.

Global observations of wind fields in the atmosphere are critical for improving weather forecasts, forecasting the trajectory of atmospheric pollutants and pathogens, and better understanding the dynamics of the atmosphere.<sup>28</sup> Many instrument and mission designs have been proposed or developed to measure

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<sup>25</sup>InSAR measurements of strain over wide geographic areas would also complement the continuous GPS point measurements being collected along the western edge of the United States, Mexico, and Canada through the Plate Boundary Observatory component of the NSF EarthScope initiative.

<sup>26</sup>National Research Council, *Review of EarthScope Integrated Science*, National Academy Press, Washington, D.C., 2001.

<sup>27</sup>National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., 2002, <<http://solidearth.jpl.nasa.gov/seswg.html>>; National Research Council, *Review of NASA's Solid-Earth Science Strategy*, The National Academies Press, Washington, D.C., 2004.

<sup>28</sup>R.M. Atlas, "Atmospheric Observations and Experiments to Assess Their Usefulness in Data Assimilation," *J. Meteorol. Soc. Jpn.* 75: 111-130, 1997; W.E. Baker, G.D. Emmitt, F. Robertson, R.M. Atlas, J.E. Molinari, D.A. Bowdle, J. Paegle, R.M. Hardesty, R.T. Menzies, T.N. Krishnamurti, R.A. Brown, M.J. Post, J.R. Anderson, A.C. Lorenc, and J. McElroy, "LIDAR-measured Winds from Space: A Key Component for Weather and Climate Prediction," *Bull. Am. Meteorol. Soc.* 79: 581-599, 1998.

the global wind field using active remote sensing techniques. In 2008, the European Space Agency will launch its Earth Explorer Atmospheric Dynamics mission (ADM-Aeolus)<sup>29</sup> to measure winds in the troposphere using an ultraviolet laser radar (lidar). In the United States, active remote sensing techniques for such measurements are not yet at a comparable level of technology readiness.<sup>30</sup>

**The committee recommends that NASA significantly expand existing technology development programs to ensure that new enabling technologies for new observational capabilities, including interferometric synthetic aperture radar, wide-swath ocean altimetry, and wind lidar, are available to support potential mission starts over the coming decade.**

### REINVIGORATE THE NASA EARTH EXPLORER MISSIONS PROGRAM

Satisfying tomorrow's critical societal needs requires us to do exploratory basic science today. In the 1990s, NASA introduced an innovative science mission program called Earth Explorers to do just that. The scientific community has been deeply engaged in planning the Earth System Science Pathfinder (ESSP) missions that fall within the Earth Explorer program. NASA developed its ESSP program as "an innovative approach for addressing Global Change Research by providing periodic 'Windows of Opportunity' to accommodate new scientific priorities and expand community participation in NASA's Earth Science activities. The program is characterized by relatively low to moderate cost, small to medium sized missions that are capable of being built, tested and launched in a short time interval."<sup>31</sup> ESSP missions were intended to be launched at a rate of one or more per year.<sup>32</sup> Today, Earth Explorers are being delayed, and there is no comparable program targeted to generate new science.

Explorer-class missions are intended to provide more frequent access to space and to allow for experimentation with new technologies.<sup>33</sup> By accepting a higher risk of failure, Explorer-class missions can be developed faster and at lower cost. Although some missions may fail, the net result will be the collection of new or unique scientific data that could not be collected by medium- and large-class missions alone. In addition, an instrument incubator program and related technology development programs foster the development of new technologies that will be used in future ESSP missions.<sup>34</sup> As a result, ESSP missions provide an impetus for advancing longer-term spaceborne measurement programs. At the same time, these smaller missions provide opportunities to train and maintain personnel needed for future missions.<sup>35</sup>

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<sup>29</sup>See <<http://www.esa.int/esaLP/aeolus.html>>.

<sup>30</sup>See, for example, Space Readiness Coherent Lidar Experiment (SPARCLE), at <<http://www.ghcc.msfc.nasa.gov/sparcle/sparcle.html>>. Also see presentation to NASA by M.J. Kavaya, U.N. Singh, and F. Amzajerdian, "A New NASA Technology Program for Risk Reduction of Space-Based Lidar Missions," January 24, 2002, at <<http://space.hsv.usra.edu/LWG/Jan02/Papers.jan02/Kavaya2.jan02.pdf>>.

<sup>31</sup>See Earth System Science Pathfinder, at <<http://earth.nasa.gov/essp/>>.

<sup>32</sup>This approach corresponds to the original intent of the Earth System Science Pathfinder program, which solicited proposals every 2 years for satellite measurements that were outside the scope of approved Earth science missions. Proposals were solicited in all Earth science disciplines, from which two missions and one alternate were selected based on scientific priority and technical readiness.

<sup>33</sup>National Research Council, *Steps to Facilitate Principal-Investigator-Led Earth Science Missions*, The National Academies Press, Washington, D.C., 2004. NASA science missions can be classified into three general categories: exploratory or explorer class (e.g., existing Earth System Science Pathfinder missions), medium class (e.g., TRMM), and large missions (e.g., EOS Terra platform). Explorer-class missions were part of NASA's Space Science Directorate, but their objectives are very similar to those of the Earth Science Directorate's ESSP program.

<sup>34</sup>National Research Council, *The Role of Small Satellites in NASA and NOAA Earth Observation Programs*, National Academy Press, Washington, D.C., 2000.

<sup>35</sup>National Research Council, *Steps to Facilitate Principal-Investigator-Led Earth Science Missions*, The National Academies Press, Washington, D.C., 2004.

### BOX 3.1 ESSP MISSIONS

The **Gravity Recovery and Climate Experiment (GRACE)** was proposed as part of ESSP-1 in 1996 and selected for development in 1997. GRACE was launched successfully in 2002. It consists of two identical spacecraft that are measuring gravity changes that are 100 to 100,000 times smaller than those measured previously, which occur over weeks compared to years, and in spans of 100 miles versus 500 miles. The mission can sense changes in gravity caused by a deep ocean current shifting or an ice sheet melting in Antarctica. It has also provided the first information about variations in groundwater storage at continental scales, an understanding that may help future missions with more advanced technology focus on global groundwater resources.

**CloudSat** and **CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations)** were proposed as part of ESSP-2 in 1998 and were confirmed by NASA headquarters and approved to proceed in December 2000. They are now scheduled for launch no earlier than July 31, 2005, and for scheduling reasons are more likely to be launched in September 2005.<sup>1</sup> CloudSat will be flown in formation with CALIPSO, which will measure cloud and aerosol composition. These satellites, together with instruments onboard the Aqua platform, will furnish data needed to evaluate and improve the way clouds are parameterized in global models, thereby contributing to better predictions of clouds and thus to the poorly understood cloud-climate feedback problem.

The **Orbiting Carbon Observatory (OCO)** was proposed as part of ESSP-3 in 2001 and selected for mission formulation in 2002. OCO will undergo a confirmation review at the end of April 2005 and is currently scheduled for launch in September 2008 (at the time of final editing of this report, the authors were pleased to learn that OCO was confirmed). Instruments on OCO will measure global concentrations of atmospheric CO<sub>2</sub>, which can be used to help unravel uncertainties about the fate of global carbon emissions and their ultimate effects on climate.

**Aquarius** was proposed as part of ESSP-3 in 2001 and selected for mission formulation in July 2002. Mission confirmation review for Aquarius is scheduled for September 2005, and launch is now likely no sooner than March 2009.<sup>2</sup> Aquarius will measure ocean surface salinity, a key variable that affects ocean circulation and from which patterns of freshwater influxes (via precipitation, river runoff, and melting of ice) and evaporation can be estimated.

**Hydros** was proposed as part of ESSP-3 in 2001, selected as an alternate mission in 2002, and selected for mission formulation in December 2003. Mission confirmation review for Hydros is planned for September 2007, and launch is now scheduled for September 2010.<sup>3</sup> Hydros will measure near-surface soil moisture, a key land surface variable that drives evapotranspiration, and hence recycling of moisture to the atmosphere. Soil moisture is also an important determinant of flood susceptibility and can be used as a drought indicator.

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<sup>1</sup>Deborah Vane, Jet Propulsion Laboratory, personal communication, April 5, 2005.

<sup>2</sup>Gary Lagerloef, Earth & Space Research, personal communication, April 22, 2005.

<sup>3</sup>Dara Entekhabi, Massachusetts Institute of Technology, personal communication, March 30, 2005.



Seven missions have been selected since the ESSP program was initiated in the mid 1990s. Of these, one is collecting data, one (the Vegetation Canopy Lidar mission) was dropped due to concerns about technological readiness, and five are scheduled for launch. The active and planned missions are described in Box 3.1. All of these missions will provide global observations that are difficult or impossible to collect using in situ technologies and that will address gaps in scientific understanding of the Earth system. Many will yield data that will help to reduce uncertainties in the understanding of the climate system, in direct support of the U.S. Climate Change Science Program. In addition, missions including CloudSat and CALIPSO are poised to make significant contributions to the reduction of risk from natural hazards, while missions such as Hydros play a significant role in bridging the gap between research and operations.

Despite the clear successes of the ESSP missions to date and the numerous benefits of the program in terms of technology development, fostering exploratory research, and training new generations of remote sensing scientists, NASA has delayed releasing the announcement of opportunity for the next generation of ESSP missions.<sup>36</sup> The committee views this delay with great concern. The committee is also concerned that all of the ESSP-3 missions (OCO, Aquarius, and Hydros) have been delayed, apparently because of inadequate funding, and the latter two now have exceedingly long development times, particularly given their relatively small size and budget.

**The committee supports continuation of a line of Explorer-class missions directed toward advancing the understanding of Earth and developing new technologies and observational capabilities, and urges NASA to:**

- **Increase the frequency of Explorer selection opportunities and accelerate the ESSP-3 missions by providing sufficient funding for at least one launch per year, and**
- **Release an ESSP-4 announcement of opportunity in FY 2005.**

## **STRENGTHEN BASELINE CLIMATE OBSERVATIONS AND CLIMATE DATA RECORDS**

### **Baseline Climate Observations**

It is essential that we know how and why Earth's climate is changing. Considerations of Earth's variable and changing climate increasingly affect government and business decisions that have large financial consequences. These decisions cannot be made wisely without accurate knowledge of the climate today and how it is changing, or without the capability to predict what it will be in the future. Current and planned observing systems are inadequate for this task.

The committee is pleased that a critical near-term objective for both GEOSS and the CCSP is to establish baseline observations from which to describe climate variability and change.<sup>37</sup> Such baseline observations provide a means of monitoring climate change and testing climate models and forecasts. Two examples demonstrate the importance of long-term, accurate measurements of key observables: (1) the

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<sup>36</sup>According to the NASA ESSP Web site at <<http://earth.nasa.gov/essp/>>, a draft announcement of opportunity was expected in the summer of 2004; this site now states that the announcement will not be out before December 2004. The announcement had not been made when the prepublication copy of this report was released (May 2005).

<sup>37</sup>See Climate Change Science Program and Subcommittee on Global Change Research, *Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Years 2004 and 2005*, 2004, at <<http://www.usgcrp.gov/usgcrp/Library/ocp2004-5/ocp2004-5.pdf>>; see also Ad-hoc Group on Earth Observations, *Global Earth Observing System of Systems: 10-Year Implementation Plan Reference Document*, GEO204, ESA Publications Division, The Netherlands, 2005, at <<http://earthobservations.org/docs/GEO204%20Final%20Draft%20Reference%20Document.pdf>>.

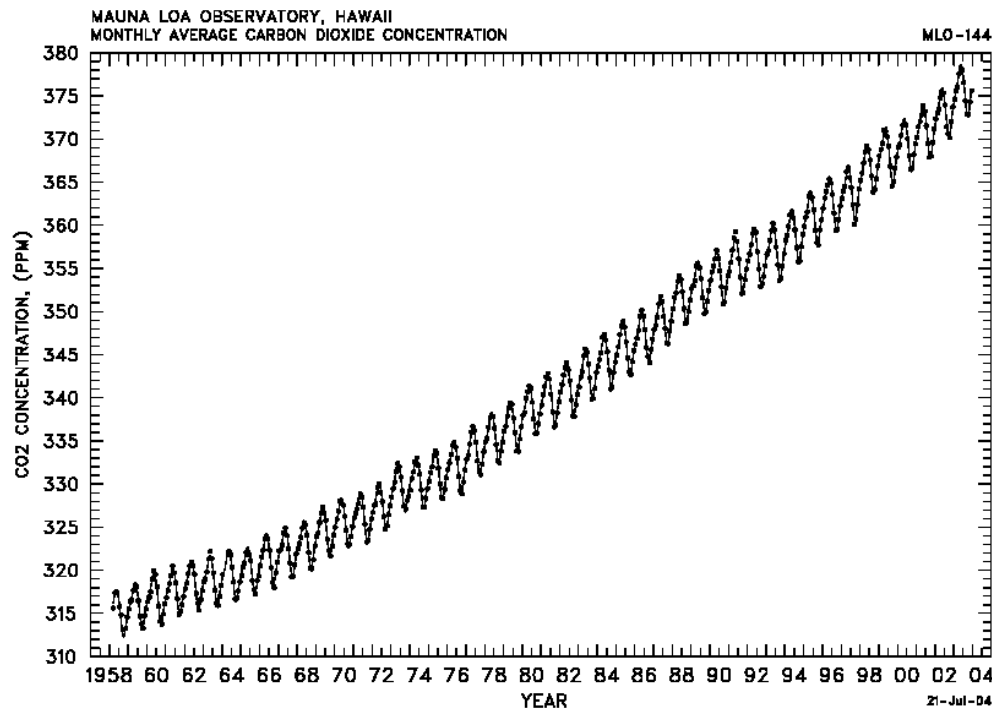


FIGURE 3.1 Carbon dioxide measured at Mauna Loa since 1958. This is the longest record of carbon dioxide measurements. SOURCE: C.D. Keeling and T.P. Whorf, "Atmospheric CO<sub>2</sub> Records from Sites in the SIO Air Sampling Network," in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., 2004.

trend of CO<sub>2</sub> concentrations measured at Mauna Loa by Charles Keeling and associates since 1958, and (2) the observation of surface and atmospheric mean temperature, which is based on various instrument records (Figure 3.1 and Plate 3). Both records show that trends in global indicators are far more informative and compelling than single values. However, the uncertainty associated with the two trends is vastly different. The CO<sub>2</sub> record is tied to absolute standards, open to the scientific community for scrutiny, and incontrovertible. Virtually all scientists agree that carbon dioxide in the atmosphere has been increasing over this period to the accuracy reported in the Keeling record. In contrast, the temperature record contains significant uncertainty, and there have been serious questions in the scientific community over the past two decades about (1) how much and where the global atmosphere is warming and (2) whether that record can distinguish between different model projections of climate change.<sup>38</sup>

The answers to such questions have significant policy implications. For example, a doubling of CO<sub>2</sub> is forecast to increase global average temperatures by 1.5 to 5°C, but to increase regional temperatures over

<sup>38</sup>National Research Council, *Improving the Effectiveness of U.S. Climate Modeling*, National Academy Press, Washington, D.C., 2001; Climate Change Science Program and Subcommittee on Global Change Research, *Strategic Plan for the U.S. Climate Change Science Program*, Washington, D.C., 2003; National Research Council, *Implementing Climate and Global Change Research: A Review of the Final U.S. Climate Change Science Program Strategic Plan*, The National Academies Press, Washington, D.C., 2004.

populated continental zones of the mid-to-high latitudes of the Northern Hemisphere by 4 to 10°C.<sup>39</sup> These changes are, by any measure, rapid and important to people, societies, and the environment, and they underscore the need for decision support tools based on a foundation of tested and trusted baseline global climate observations and on credible long-term climate forecasts.

The design of climate observing and monitoring systems must ensure the establishment of global long-term climate records that are of high accuracy and precision,<sup>40</sup> tested for systematic errors on-orbit, and tied to irrefutable absolute standards by independent methods. It is essential that the accuracy of the benchmark observations enable the climate record archived today to be verified by future generations in any country. Finally, to meet societal objectives, the long-term record must not be susceptible to compromise by interruptions.

A full complement of baseline observations will be addressed by the committee in its final report; here the committee indicates some of the high-priority global climate benchmark observations from space:

- *Atmospheric water vapor and temperature* measured globally from the surface to the mid stratosphere with high vertical resolution tied to absolute international standards constitute the foundation of climate records.<sup>41</sup> High-vertical-resolution (200-meter) temperature to an accuracy of 0.1 K in the lower stratosphere and upper troposphere, and temperature and water vapor in the middle and lower troposphere with unbiased global coverage in all weather, can be obtained using the GPS radio occultation technique.<sup>42</sup>
- *Absolute spectrally resolved infrared radiance* emitted from Earth to space measured to high accuracy (0.1 K) against NIST standards on-orbit provides an absolute climate record that separates radiative forcing from the response of the atmosphere with respect to temperature, water vapor, and cloud structure.<sup>43</sup>

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<sup>39</sup>Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001.

<sup>40</sup>It is important to distinguish between accuracy and precision. "Accuracy" refers to the measure of the non-random, systematic error, or bias, that defines the offset between the measured value and the true value as referenced to the absolute standard defined at the National Institute of Standards and Technology (NIST). "Precision," on the other hand, refers to the measure of repeatability without reference to an international standard. Long-term records built on precision (or stability, reproducibility, repeatability, consistency, continuity, data record overlap, etc.) rely on efforts to reconcile time- or instrument-dependent biases without an international standard. They are thereby compromised by lack of continuity in the data record and are open to criticism.

<sup>41</sup>National Research Council, *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, The National Academies Press, Washington, D.C., pp. 6 and 111, 2005; Climate Change Science Program, *Strategic Plan for the U.S. Climate Change Science Program*, U.S. Climate Change Science Program, Washington, D.C., p. 127, 2003; National Institute of Standards and Technology, *Satellite Instrument Calibration for Measuring Global Climate Change*, G. Ohring, B. Wielicki, R. Spencer, B. Emery, and R. Datla, eds., Report of a Workshop at the University of Maryland Inn and Conference Center, College Park, Md., November 12-14, 2002, NISTIR 7047, Washington, D.C., 2002.

<sup>42</sup>The World Meteorological Organization (WMO) has recommended an operational constellation of radio-occultation satellites as part of the Global Climate Observing System (GCOS). See WMO Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC, GCOS-92 (WMO/TD No. 1219), Geneva, 2004.

<sup>43</sup>National Research Council, *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, The National Academies Press, Washington, D.C., pp. 6 and 111, 2005; Climate Change Science Program, *Strategic Plan for the U.S. Climate Change Science Program*, U.S. Climate Change Science Program, Washington, D.C., p. 127, 2003; National Institute of Standards and Technology, *Satellite Instrument Calibration for Measuring Global Climate Change*, G. Ohring, B. Wielicki, R. Spencer, B. Emery, and R. Datla, eds., Report of a Workshop at the University of Maryland Inn and Conference Center, College Park, Md., November 12-14, 2002, NISTIR 7047, Washington, D.C., 2002.; D.B. Pollock, T.L. Murdock, R.U. Datla, and A. Thompson, "Radiometric Standards in Space: The Next Step," *Metrologia* 37: 403-406, 2000; D.B. Pollock, T.L. Murdock, R.A. Datla, and A. Thompson, "Data Uncertainty Traced to S.I. Units: Results Reported in the International System of Units," *Int. J. Remote Sensing* 24: 225-235, 2003; World Meteorological Organization, GCOS-7: Report of the GCOS Space-based Observation Task Group, WMO/TD No. 641, Darmstadt, Germany, p. 4, 1994; World Meteorological Organization, Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC, GCOS-92, WMO/TD No. 1219, Geneva, 2004.



- *Absolute incident and reflected solar irradiances* define solar forcing, which constitutes the fundamental long-term record of net energy received by the Earth system. Benchmark observations of total solar irradiance and spectrally resolved solar irradiance to an accuracy of 0.03 percent referenced to NIST standards are required to elucidate the origin of climate change. The incident component ties solar output to an absolute scale,<sup>44</sup> and the reflected component defines the quantitative impact of spatially resolved changes in snow cover, sea ice, aerosol properties, and land use on the flux of energy returned to space.<sup>45</sup>

**The committee recommends that NASA, NOAA, and other agencies as appropriate accelerate efforts to create a sustained, robust, integrated observing system that includes at a minimum an essential baseline of climate observations, including atmospheric temperature and water vapor, spectrally resolved Earth radiances, and incident and reflected solar irradiance.**

### Climate Data Records and NPOESS

The NRC and others have recommended that NOAA embrace its new mandate to understand climate variability and change by asserting national leadership in applying new approaches to generate and manage satellite climate data records (CDRs), developing new community relationships, and ensuring the long-term accuracy of satellite data records.<sup>46</sup> Climate data records are time series measurements of sufficient length and accuracy to determine climate variability and change. NOAA has stated its intention to use NPOESS to create CDRs.<sup>47</sup> However, the production, distribution, and stewardship of long-term climate records and the associated systematic testing and improvement of climate forecasts cannot be accomplished through the current NPOESS program or its data system architecture. As discussed above, baseline climate observations will be required, other satellite data records will have to be incorporated, and biases will have to be removed through testing for systematic errors on-orbit using independent techniques pinned to NIST absolute standards. These tasks will be sufficiently complex that a climate data and information system (a "Climate Central") will be needed, analogous to the operational weather prediction centers for environmental data records.<sup>48</sup> The Climate Central would benefit from having its own advisory council with international participation; moreover, the U.S.-funded Climate Central could become a node within an international virtual Climate Central. An associated data analysis and research program is also needed. The CCSP and Global Earth Observation initiatives provide a possible manage-

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<sup>44</sup>National Research Council, *Solar Influences on Global Change*, National Academy Press, Washington, D.C., p. 1, 1994; Intergovernmental Panel on Climate Change, *Climate Change 1994, Radiative Forcing of Climate Change and an Evaluation of the IPCC 1992 IS92 Emission Scenarios*, J.T. Houghton, L.G. Meira Filho, J.P. Bruce, H. Lee, B.A. Callander, and E.F. Haites, eds., Cambridge University Press, Cambridge, 1995; R.C. Wilson, "Total Solar Irradiance Trend in Solar Cycles 21 and 22," *Science* 277: 1963-1965, 1997.

<sup>45</sup>National Research Council, *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, The National Academies Press, Washington, D.C., p. 112, 2005.

<sup>46</sup>National Research Council, *Climate Data Records from Environmental Satellites: Interim Report*, The National Academies Press, Washington, D.C., 2004. See also congressional testimony of Dr. Mark Abbott at <<http://www.house.gov/science/hearings/ets02/jul24/abbott.htm>>.

<sup>47</sup>See <<http://projects.osd.noaa.gov/NDE/pub-docs/NDE-1PgDescript.pdf>> and NOAA's 2003 white paper plan to create CDRs at <[http://cimss.ssec.wisc.edu/itwg/groups/climate/Creating\\_CDRs\\_from\\_NOAA\\_Satellites\\_White\\_Paper\\_18\\_Aug.pdf](http://cimss.ssec.wisc.edu/itwg/groups/climate/Creating_CDRs_from_NOAA_Satellites_White_Paper_18_Aug.pdf)>.

<sup>48</sup>A.M. Goldberg, *Environmental Data Production and Delivery for NPOESS*, The MITRE Corporation, Work performed under NOAA contract 50-SPNA-9-00010; see <[http://www.mitre.org/work/tech\\_papers/tech\\_papers\\_02/goldberg\\_environmental/goldberg\\_environmental.pdf](http://www.mitre.org/work/tech_papers/tech_papers_02/goldberg_environmental/goldberg_environmental.pdf)>.

ment structure through which NOAA could work to ensure that long-term climate records are created and maintained.

**The committee recommends that NOAA, working with the Climate Change Science Program and the international Group on Earth Observations, create a climate data and information system to meet the challenge of ensuring the production, distribution, and stewardship of high-accuracy climate records from NPOESS and other relevant observational platforms.**

## 4

# Summary and Next Steps

Global observations of Earth are essential to understanding how the planet is changing and the implications of these changes for society. In the coming decades, society's prosperity and security will depend increasingly on Earth information, predictions, and warnings, which, in turn, rely fundamentally on sustained observations of the Earth system, linked to land and ocean observations and decision-support structures. Indeed, the need to improve this linkage was a key motivation for creating the Global Earth Observing System of Systems (GEOSS), which was initiated under U.S. leadership. During the next year the National Research Council's Committee on Earth Science and Applications from Space will carry out its decadal study to recommend new observing systems for Earth science research and operations. The structure of its panels roughly reflects the socioeconomic benefit areas targeted by GEOSS (Table 4.1), an arrangement that will help ensure that the committee's recommended Earth research and observations can be applied for the specific benefit of society—now and for future generations.

**TABLE 4.1 Relationship of NRC Panel Themes with GEOSS Socioeconomic Benefit Areas**

Decadal Survey Panel Theme	GEOSS Socio-Economic Benefit Area
Earth science applications and societal needs	<ul style="list-style-type: none"><li>• Supporting sustainable agriculture and combating desertification</li><li>• Reducing loss of life and property from natural and human-induced disasters</li></ul>
Ecosystem health and biodiversity	<ul style="list-style-type: none"><li>• Improving the management and protection of terrestrial, coastal, and marine ecosystems</li><li>• Understanding, monitoring, and conserving biodiversity</li></ul>
Weather Climate variability and change	<ul style="list-style-type: none"><li>• Improving weather information, forecasting, and warning</li><li>• Understanding, assessing, predicting, mitigating, and adapting to climate variability and change</li></ul>
Water resources and the global hydrologic cycle	<ul style="list-style-type: none"><li>• Improving water resource management through better understanding of the water cycle</li></ul>
Human health and security	<ul style="list-style-type: none"><li>• Understanding environmental factors affecting human health and well-being</li></ul>
Solid-Earth hazards, resources, and dynamics	<ul style="list-style-type: none"><li>• Improving management of energy resources</li></ul>

# Appendixes



# A

## Statement of Task

The Space Studies Board will organize a study, “Earth Observations from Space: A Community Assessment and Strategy for the Future.” The study will generate consensus recommendations from the Earth and environmental science and applications community regarding science priorities, opportunities afforded by new measurement types and new vantage points, and a systems approach to space-based and ancillary observations that encompasses the research programs of NASA and the related operational programs of NOAA.

During this study, the committee will conduct the following tasks.

1. Review the status of the field to assess recent progress in resolving major scientific questions outlined in relevant prior NRC, NASA, and other relevant studies and in realizing desired predictive and applications capabilities via space-based Earth observations;
2. Develop a consensus of the top-level scientific questions that should provide the focus for Earth and environmental observations in the period 2005-2015;
3. Take into account the principal federal- and state-level users of these observations and identify opportunities and challenges to the exploitation of the data generated by Earth observations from space.
4. Recommend a prioritized list of measurements, and identify potential new space-based capabilities and supporting activities within NASA [Earth Science Enterprise] and NOAA [National Environmental Satellite, Data, and Information Service] to support national needs for research and monitoring of the dynamic Earth system during the decade 2005-2015. In addition to elucidating the fundamental physical processes that underlie the interconnected issues of climate and global change, these needs include: weather forecasting, seasonal climate prediction, aviation safety, natural resources management, agricultural assessment, homeland security, and infrastructure planning.
5. Identify important directions that should influence planning for the decade beyond 2015. For example, the committee will consider what ground-based and in-situ capabilities are anticipated over the next 10-20 years and how future space-based observing systems might leverage these capabilities. The committee will also give particular attention to strategies for NOAA to evolve current capabilities while

meeting operational needs to collect, archive, and disseminate high quality data products related to weather, atmosphere, oceans, land, and the near-space environment.

The committee will address critical technology development requirements and opportunities; needs and opportunities for establishing and capitalizing on partnerships between NASA and NOAA and other public and private entities; and the human resource aspects of the field involving education, career opportunities, and public outreach. A minor but important part of the study will be the review of complementary initiatives of other nations in order to identify potential cooperative programs.



## B

# Acronyms and Abbreviations

ACRIM	Active Cavity Radiometer Irradiance Monitor
APS	Advanced Polarimetric Sensor
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CCSP	Climate Change Science Program
CDR	climate data record
CFC	chlorofluorocarbon
CMIS	Conical Scanning Microwave Imager/Sounder
EOS	Earth Observing System
ERB	Earth Radiation Budget
ERBS	Earth Radiation Budget Satellite
ESSP	Earth System Science Pathfinder
FY	fiscal year
GEOSS	Global Earth Observing System of Systems
GIFTS	Geostationary Imaging Fourier Transform Spectrometer
GOES	Geostationary Operational Environmental Satellite
GOES-R	Geostationary Operational Environmental Satellite-R (the next generation of GOES satellites)
GPM	Global Precipitation Measurement (mission)
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
IBEX	Interstellar Boundary Experiment
InSAR	interferometric synthetic aperture radar

IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LDCM	Landsat Data Continuity Mission
lidar	light detection and ranging (laser radar)
MTPE	Mission to Planet Earth
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Program
NRC	National Research Council
NSCAT	NASA Scatterometer
OCO	Orbiting Carbon Observatory
OLI	Operational Land Imager
OSTM	Ocean Surface Topography Mission
OSTP	Office of Science and Technology Policy
R&A	research and analysis
SLC	scan line corrector
SORCE	Solar Radiation and Climate Experiment
SPARCLE	Space Readiness Coherent Lidar Experiment
TIM	Total Irradiance Monitor
TRMM	Tropical Rainfall Measuring Mission
USGS	U.S. Geological Survey
WMO	World Meteorological Organization

## C

# Biographies of Committee Members and Staff

RICHARD A. ANTHES, *Co-chair*, is president of the University Corporation for Atmospheric Research, Boulder, Colorado. His research has focused on the understanding of tropical cyclones and mesoscale meteorology and on the radio occultation technique for sounding Earth's atmosphere. Dr. Anthes is a fellow of the AMS and the AGU, and is a recipient of the AMS Clarence I. Meisinger Award and the Jule G. Charney Award. In 2003 he was awarded the Friendship Award by the Chinese government, the most prestigious award given to foreigners, for his contributions over the years to atmospheric sciences and weather forecasting in China. His National Research Council (NRC) service includes chairing the National Weather Service Modernization Committee from 1996 to 1999 and the Committee on NASA-NOAA Transition of Research to Operations in 2002-2003.

BERRIEN MOORE III, *Co-chair*, is a professor and director of the Institute for the Study of Earth, Oceans, and Space, University of New Hampshire. A professor of systems research, he received the university's 1993 Excellence in Research Award and was named University Distinguished Professor in 1997. Moore's research focuses on the carbon cycle, global biogeochemical cycles, and global change as well as policy issues in the area of the global environment. He has served on several NASA advisory committees and in 1987 chaired the NASA Space and Earth Science Advisory Committee. Dr. Moore led the IGBP Task Force on Global Analysis, Interpretation, and Modeling (GAIM) prior to serving as chair of the overarching Scientific Committee of the International Geosphere-Biosphere Programme (IGBP). As chair of the SC-IGBP (1998-2002), Dr. Moore served as a lead author of the Intergovernmental Panel on Climate Change's (IPCC's) Third Assessment Report, which was released in Spring 2001. He chaired the July 2001 Open Science Conference on Global Change in Amsterdam and is one of the four architects of the Amsterdam Declaration on Global Change. Dr. Moore has contributed actively to committees at the NRC; most recently, he served as chair of the NRC Committee on International Space Programs. From 1987 to 1992, he was a member of the NRC Board on Global Change, and he chaired the NRC Committee on Global Change Research from 1995 to 1998. Dr. Moore currently serves on the Science Advisory Board of NOAA and the Advisory Board of the National Center for Atmospheric Research.

JAMES G. ANDERSON is the Philip S. Weld Professor in the Departments of Chemistry and Chemical Biology, Earth and Planetary Sciences, and the Division of Engineering and Applied Sciences at Harvard University. His interests include chemistry, the dynamics and radiation of Earth's atmosphere in the context of climate, experimental and theoretical studies of the kinetics and photochemistry of free radicals, and the development of new methods for in situ and remote observations of processes that control chemical and physical coupling within Earth's atmosphere. He has served on the NRC Committee on Global Change Research (1996-2002), the Committee on Atmospheric Chemistry (1992-1995), and the Board on Atmospheric Sciences and Climate (1986-1989). Dr. Anderson is a member of the National Academy of Sciences.

SUSAN K. AVERY is a professor of electrical and computer engineering and the former director of the Cooperative Institute for Research in Environmental Sciences. Currently, Dr. Avery is the vice chancellor for research and dean of the University of Colorado, Boulder, Graduate School. Her research program utilizes ground-based Doppler radar techniques for observing the neutral atmosphere. Dr. Avery is currently the president of the American Meteorological Society. She has served as chair of the U.S. National Committee for the International Union of Radio Science; chair of the National Science Foundation Geosciences Advisory Committee; Scientific Discipline Representative and URSI Representative for SCOSTEP; and commissioner of the American Meteorological Society. She is a fellow of the AMS and the IEEE. Her NRC service includes the Committee on NOAA NESDIS Transition from Research to Operations (vice chair, 2002-2004) and the Board on Atmospheric Sciences and Climate (1997-2001). She currently serves as a member of the Committee on Strategic Guidance for NSF's Support of the Atmospheric Sciences.

ERIC J. BARRON is dean of the College of Earth and Mineral Sciences and a distinguished professor of geosciences at the Pennsylvania State University. Before becoming dean, Barron was director of the EMS Environment Institute. Dr. Barron's research interests are in the areas of climatology, numerical modeling, and Earth history. He is a fellow of the American Geophysical Union, the American Association for the Advancement of Science, and the American Meteorological Society. He currently serves as chair of the NRC Committee on Metrics for Global Change Research. Dr. Barron's previous NRC service includes multiple terms on the NRC Board on Atmospheric Sciences and Climate (chair, 2000-2003; co-chair, 1997-1998; member, 1995-1996) and the Committee on Climate Research (member 1987-1990; chair, 1990-1996). Dr. Barron also served on the Committee on Science of Climate Change (2001), the Committee on Grand Challenges in the Environmental Sciences (1998-2000), the Task Group on Assessment of NASA Plans for Post-2000 Earth Observing Missions (1999), the Committee on the Human Dimensions of Global Change (1991-1997), and the Board on Global Change Research (1990-1994). From 1994 to 1997 Dr. Barron chaired the NASA Earth Observing System, Science Executive Committee and in 1993 chaired the NASA Earth Science and Applications Advisory Committee.

OTIS B. BROWN is dean and professor of meteorology and physical oceanography of the Rosenstiel School of Marine and Atmospheric Science, University of Miami. Dr. Brown's specialties are satellite oceanography, development of quantitative methods for the processing and use of satellite remotely sensed observations to study ocean variability, focused on ocean color and infrared observations. His experimental focus has been on western boundary current variability for the studies in the Somali Current, Gulf Stream, Agulhas, and Brazil Confluence regions. More recently this effort has expanded to include development of basin-scale climatologies for sea-surface temperature and color fields. Dr. Brown has published widely on the application of satellite observations to the understanding of oceanic processes and has served on numerous national and international scientific committees, including the U.S. Joint Global

Ocean Flux Study, the Joint Committee on Global Ocean Observing Systems, and the NOAA Advisory Panel on Climate and Global Change. His most recent awards include NASA's Public Service Group Achievement Award and election as a fellow of the American Association for the Advancement of Science. Dr. Brown's NRC service includes membership on the Ocean Studies Board (1998-2000), the Panel on Near-Term Development of Operational Ocean Observations (1991-1992), the Advisory Panel for the Tropical Ocean/Global Atmosphere (TOGA) program (1985-1991), and the Committee on Earth Studies (1996-1999).

SUSAN L. CUTTER is the director of the Hazards Research Laboratory and a Carolina Distinguished Professor of Geography at the University of South Carolina. Dr. Cutter has worked in the risk and hazards fields for more than 25 years and is a nationally recognized scholar in this field. She has provided expert advice to numerous governmental agencies in the hazards and environmental fields, including NASA, FEMA, and NSF. She has also authored or edited 11 books and more than 75 peer-reviewed articles and book chapters. In 1999, Dr. Cutter was elected as a fellow of the American Association for the Advancement of Science (AAAS), and she was president of the Association of American Geographers in 1999-2000. She currently serves on the NRC Geographical Sciences Committee, the Committee on Disaster Research in the Social Sciences, and the Panel on Social and Behavioral Science Research Priorities for Environmental Decision Making.

WILLIAM B. GAIL is vice president of Mapping and Photogrammetric Solutions at Vexcel Corporation, where he leads a global organization responsible for a wide range of systems and services associated with Earth information. Prior to joining Vexcel, he was director of Earth Science Advanced Programs at Ball Aerospace, where he led the development of spaceborne instrument and mission concepts for Earth science and meteorology. Dr. Gail received his undergraduate degree in physics and his Ph.D. in electrical engineering from Stanford University, focusing his research on the physics of Earth's magnetosphere. During this period, he spent a year as a field scientist at South Pole Station, managing experiments on cosmic rays and upper atmospheric physics. Dr. Gail is currently on the board of directors of Peak Weather Resources, Inc., a small company formed to transition weather research to the commercial market. He is also a member of the Administrative Committee of the IEEE Geoscience and Remote Sensing Society and founder of its Industry Liaison Group. In addition, he is a member of the NASA Earth Science and Applications from Space Strategic Roadmap Committee. He is currently a member of the NRC Committee on Earth Studies and previously served on the Task Group on Principal Investigator-Led Earth Science Missions (2001-2003), the Committee on NASA-NOAA Transition from Research to Operations (2002-2003), and the Committee to Review the NASA Earth Science Enterprise Strategic Plan (2003).

BRADFORD H. HAGER is the Cecil and Ida Green Professor of Earth Sciences in the Earth, Atmospheric and Planetary Sciences Department at the Massachusetts Institute of Technology (MIT). Dr. Hager is best known for his research on the physics of geologic processes. He has focused his work on applying geophysical observations and numerical modeling to the study of mantle convection, the coupling of mantle convection to crustal deformation, and precision geodesy. From 1980 until he came to MIT, he was a professor of geophysics at the California Institute of Technology. Dr. Hager has chaired or been a member of several NRC committees concerned with solid-earth science. These include the U.S. Geodynamics Committee, the Geodesy Committee, the Committee for Review of the Science Implementation Plan of the NASA Office of Earth Science, and the Committee to Review NASA's Solid-Earth Science Strategy. Dr. Hager is a fellow of the AGU. He was the 2002 recipient of the Geological Society of America's Woollard Award in recognition of distinctive contributions to geology through the application of the principles and

techniques of geophysics; he also received the AGU's James B. Macelwane Award for his contributions to understanding the physics of geologic processes.

ANTHONY HOLLINGSWORTH has been a staff member of the European Centre for Medium-range Weather Forecasting (ECMWF) since 1975. From 1991 to 2003, he served as the ECMWF's head of research and deputy director. Currently he is the ECMWF's Coordinator for Global Earth-system Monitoring. He is the recipient of the 1999 American Meteorological Society's Jule G. Charney Award for "penetrating research on four-dimensional data assimilation systems and numerical models." He is a fellow of the American Meteorological Society and of the Royal Meteorological Society, and is a member of the Irish Meteorological Society. Dr. Hollingsworth served on the NRC Panel on Model-Assimilated Data Sets for Atmospheric and Oceanic Research (1989-1991).

ANTHONY C. JANETOS has been vice president of the H. John Heinz III Center for Science, Economics, and the Environment since March 2003; he joined the center as a senior fellow in June 2002. Dr. Janetos also directs the center's Global Change program. Before coming to the Heinz Center, he served as vice president for science and research at the World Resources Institute and senior scientist for the Land-Cover and Land-Use Change Program in NASA's Office of Earth Science. He was also a program scientist for NASA's Landsat 7 mission. He has had many years of experience in managing scientific research programs on a variety of ecological and environmental topics, including air pollution effects on forests, climate change impacts, land-use change, ecosystem modeling, and the global carbon cycle. He was a co-chair of the U.S. National Assessment of the Potential Consequences of Climate Variability and Change, and an author of the IPCC Special Report on Land-Use Change and Forestry, and also of the Global Biodiversity Assessment. Dr. Janetos recently served on the NRC Committee for Review of the U.S. Climate Change Science Program Strategic Plan and was a member of the Committee on Review of Scientific Research Programs at the Smithsonian Institution (2002).

KATHRYN KELLY is a principal oceanographer at the Applied Physics Laboratory of the University of Washington (UW) and a professor (affiliate) in the School of Oceanography. She is the former chair of the Air-sea Interaction/Remote Sensing (AIRS) Department at APL. Prior to her appointment at UW, Dr. Kelly worked at the Woods Hole Oceanographic Institution (WHOI), where she was part of the NASA Scatterometer (NSCAT) Science Working Team and began working with altimetric data. She is currently a member of the NASA Ocean Vector Wind Science Team and the NASA Ocean Surface Topography Science Team. At WHOI, she concentrated on the dynamics and thermodynamics of western and eastern boundary currents. Dr. Kelly's current scientific interest is primarily in the applications of large data sets, particularly from satellite sensors, to problems of climate, atmosphere-ocean interaction, and ocean circulation. She works in collaboration with numerical modelers and scientists who make in situ measurements to better understand the ocean and to improve the quality of the satellite data. Dr. Kelly has served on numerous NASA advisory committees and was a member of the NRC Panel on Statistics and Oceanography (1992-1993).

NEAL F. LANE is the Edward A. and Hermena Hancock Kelly University Professor at Rice University. He also holds appointments as senior fellow of the James A. Baker III Institute for Public Policy, where he is engaged in matters of science and technology policy, and in the Department of Physics and Astronomy, and he previously served as university provost. Dr. Lane is a nationally recognized leader in science and technology policy development and application. He has previously served as the president's assistant for science and technology, director of the White House Office of Science and Technology Policy, director of



the National Science Foundation, and chancellor of the University of Colorado at Colorado Springs. Dr. Lane is a fellow of the American Physical Society, the American Academy of Arts and Sciences, the American Association for the Advancement of Science, and the Association for Women in Science. He currently serves as chair of the NRC Committee on Transportation of Radioactive Waste, and he is also a member of the Policy and Global Affairs Committee.

DENNIS P. LETTENMAIER is a professor in the Department of Civil Engineering and the director of the Surface Water Hydrology Research Group at the University of Washington. Dr. Lettenmaier's interests cover hydroclimatology, surface water hydrology, and GIS and remote sensing. He was a recipient of ASCE's Huber Research Prize in 1990, is a fellow of the American Geophysical Union and American Meteorological Society, and is the author of over 100 journal articles. He is currently chief editor of the American Meteorological Society *Journal of Hydrometeorology*. Dr. Lettenmaier is a member of the NRC Committee on Hydrologic Science: Studies of Strategic Issues in Hydrology. He has served on other NRC committees and panels, including the Committee on Hydrologic Science: Studies in Land-Surface Hydrologic Sciences (2002-2004) and the Committee on the National Ecological Observatory Network (2003-2004).

ARAM M. MIKA<sup>1</sup> was vice president and general manager of the Advanced Technology Center in Palo Alto, California, where he led research and development for Lockheed Martin Space Systems. The Advanced Technology Center is Lockheed Martin's primary multidisciplinary R&D laboratory, with a technology portfolio that encompasses optics and electro-optics; precision control systems; guidance and navigation; materials and structures; RF, photonics, and telecommunications; cryogenics and thermal sciences; space-science instrumentation; and modeling, simulation, and information science. The Advanced Technology Center also produces payload instrumentation for space-science missions and provides technology consulting for other operating units throughout the Lockheed Martin Corporation. Prior to his career at Lockheed Martin, he was vice president of GM-Hughes Electronics (formerly Hughes Aircraft) and president of its Space Electro-Optics Business Unit, where he directed the design, development, and production of spaceborne electro-optical sensors and associated signal/data processing systems for civil space and DOD applications. These products included sensors and systems for Earth remote sensing, meteorology, planetary-exploration missions, and defense applications such as missile warning and tracking. Previously at Hughes, Mr. Mika served as vice president of the Santa Barbara Research Center and general manager of its systems division, where he led the development of space-instrument payloads for NASA, NOAA, and international customers. Mr. Mika has also been extensively engaged in numerous advisory panels, review boards, committees, and conferences on space remote sensing, including the NRC Task Group on Technology Development in NASA's Office of Space Science (1998) and the Committee on Earth Studies (1995-1998).

WARREN M. WASHINGTON is a senior scientist and head of the Climate Change Research Section in the Climate and Global Dynamics Division at the National Center for Atmospheric Research (NCAR). After completing his doctorate in meteorology at Pennsylvania State University, he joined NCAR in 1963 as a research scientist. Dr. Washington's areas of expertise are atmospheric science and climate research, and he specializes in computer modeling of Earth's climate. He serves as a consultant and advisor to a number

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<sup>1</sup>The committee notes with deep regret Aram Mika's death on May 18, 2005.



of government officials and committees on climate-system modeling. From 1978 to 1984, he served on the President's National Advisory Committee on Oceans and Atmosphere. In 1998, he was appointed to the National Oceanic and Atmospheric Administration's Science Advisory Board. In 2002, he was appointed to the Science Advisory Panel of the U.S. Commission on Ocean Policy and the National Academies' Coordinating Committee on Global Change. Dr. Washington's NRC service is extensive and includes membership on the Board on Sustainable Development (1995-1999), the Commission on Geosciences, Environment, and Resources (1992-1994), and the Board on Atmospheric Sciences and Climate (1985-1988), and his service as chair of the Panel on Earth and Atmospheric Sciences (1986-1987). He is a member of the National Science Board and currently serves as the chair. Dr. Washington is a member of the National Academy of Engineering.

MARK L. WILSON is a professor of epidemiology, director of the Global Health Program, and professor of ecology and evolutionary biology at the University of Michigan. His research and teaching cover the broad area of ecology and epidemiology of infectious diseases. After earning his doctoral degree from Harvard University in 1985, he worked at the Pasteur Institute in Dakar, Senegal (1986-1990), was on the faculty at the Yale University School of Medicine (1991-1996), and then joined the University of Michigan. Dr. Wilson's research addresses the environmental determinants of zoonotic and arthropod-borne diseases, the evolution of vector-host-parasite systems, and the analysis of transmission dynamics. He is an author of more than 120 journal articles, book chapters, and research reports and has served on numerous governmental advisory groups concerned with environmental change and health. Dr. Wilson served on the NRC Committee on Emerging Microbial Threats to Health in the 21st Century (2001-2003), the Committee on Review of NASA's Earth Science Applications Program Strategic Plan (2002), and the Committee on Climate, Ecosystems, Infectious Diseases, and Human Health (1999-2001).

MARY LOU ZOBACK is a senior research scientist with the U.S. Geological Survey's Earthquake Hazards Team, Menlo Park, Calif. She is a respected geophysicist recognized for her work on the relationship between earthquakes and the state of stress in Earth's crust. From 1986 to 1992, Dr. Zoback created and led the World Stress Map project, an effort that actively involved 40 scientists from 30 different countries, with the objective of interpreting a wide variety of geologic and geophysical data on the present-day tectonic stress field. Dr. Zoback was awarded the American Geophysical Union's Macelwane Award in 1987 for "significant contributions to the geophysical sciences by a young scientist of outstanding ability," and a USGS Gilbert Fellowship Award (1990-1991). She is a former president of both the Geological Society of America and AGU's Tectonophysics Section and was a member of the AGU Council. Dr. Zoback has extensive Academies-wide service and currently serves on the NAS Council and the National Academies' Committee on Science, Engineering, and Public Policy. She served as a member of the Board on Radioactive Waste Management (1997-2000) and of the Commission on Geosciences, Environment, and Resources (1998-2000). Dr. Zoback is a member of the National Academy of Sciences.

### **Staff**

ARTHUR CHARO, study director, received his Ph.D. in physics from Duke University in 1981 and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. Dr. Charo then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a fellow from 1985 to 1988. From 1988 to 1995, he worked in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment (OTA). He has been a senior program officer at the Space Studies Board (SSB) of the National Research Council (NRC)

since OTA's closure in 1995. Dr. Charo's principal responsibilities at the SSB are to direct the activities of the NRC Committee on Earth Studies and the NRC Committee on Solar and Space Physics. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and was the American Institute of Physics' 1988-1989 AAAS Congressional Science Fellow. In addition to directing studies that have resulted in some 22 reports from the NRC, he is the author of research papers in the field of molecular spectroscopy; reports to Congress on arms control and space policy; and the monograph *Continental Air Defense: A Neglected Dimension of Strategic Defense* (University Press of America, 1990).

ANNE M. LINN, senior program officer, received her Ph.D. in geology from the University of California, Los Angeles, in 1991. Following a postdoctoral research position in geochemistry at the University of California, Berkeley, and a visiting research position at the Carnegie Institution of Washington for one year, she joined the National Academies' Board on Earth Sciences and Resources in 1993. There she has worked on a wide variety of studies in geophysics, Earth observing systems, and data, culminating in 19 National Research Council reports. Dr. Linn also volunteers for two committees under the International Council for Science (ICSU). She is the secretary of the ICSU Panel on World Data Centers and a member of the ICSU ad hoc Committee on Data and Information.

THERESA M. FISHER is a senior program assistant with the Space Studies Board. During her 25 years with the National Research Council (NRC) she has held positions in the executive, editorial, and contract offices of the National Academy of Engineering, as well as positions with several NRC boards, including the Energy Engineering Board, the Aeronautics and Space Engineering Board, the Board on Atmospheric Sciences and Climate, and the Marine Board.

CATHERINE A. GRUBER is an assistant editor with the Space Studies Board. She joined SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and has also worked as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.



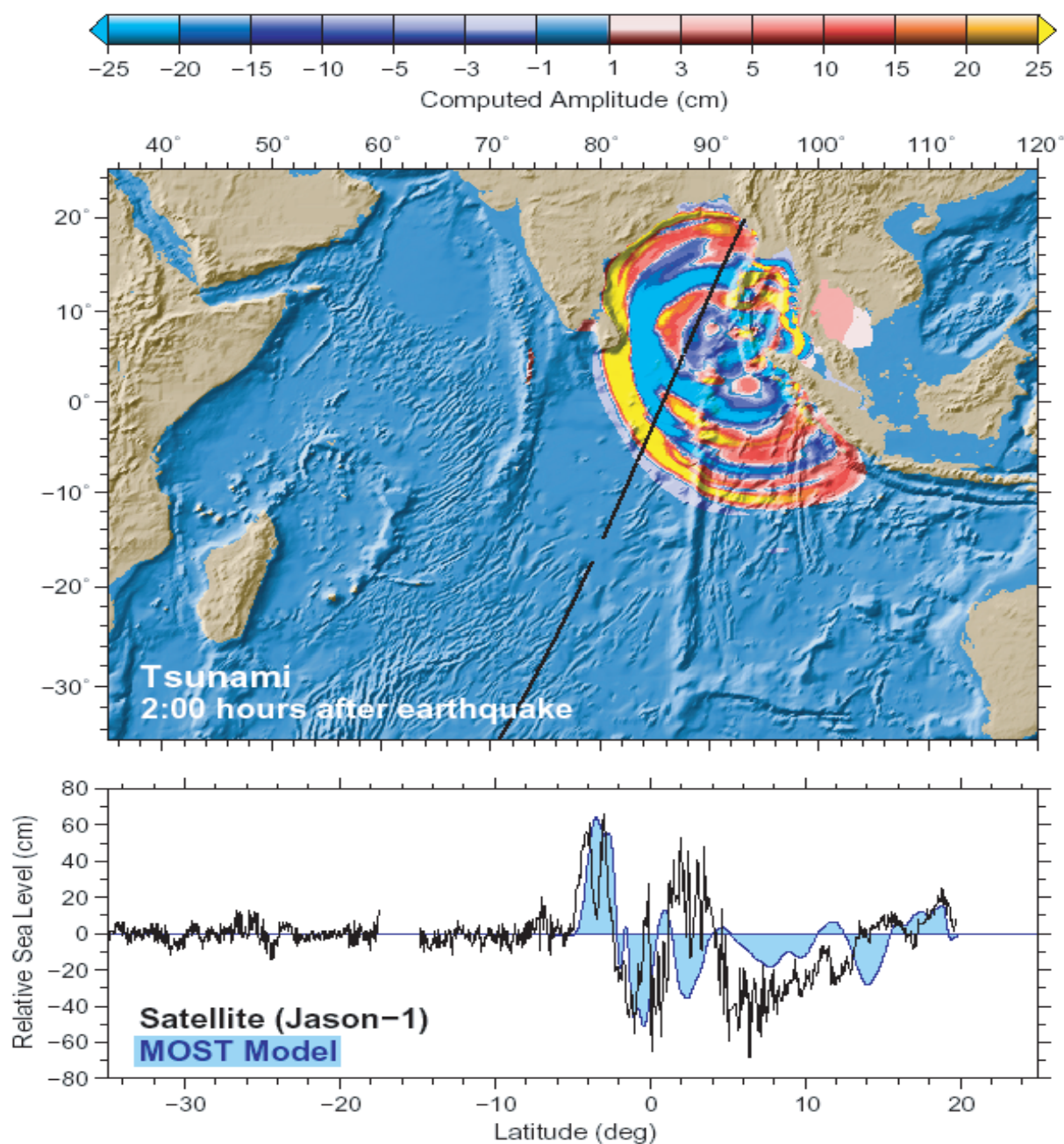


PLATE 1 (Top) Model of the anomalous water height (warm colors are increases in height and cool colors are decreases in height) caused by the deep-water propagation of the tsunami. (Bottom) comparison of the altimetry data (black line) from the Jason-1 satellite 2 hours after the event with the model result (blue line). SOURCE: NOAA's Pacific Marine Environmental Laboratory. For further information, see NOAA, NOAA News Online, "Scientists Able to Measure Tsunami Height from Space," 2005, at <http://www.noaa.gov/stories2005/s2365.htm>.

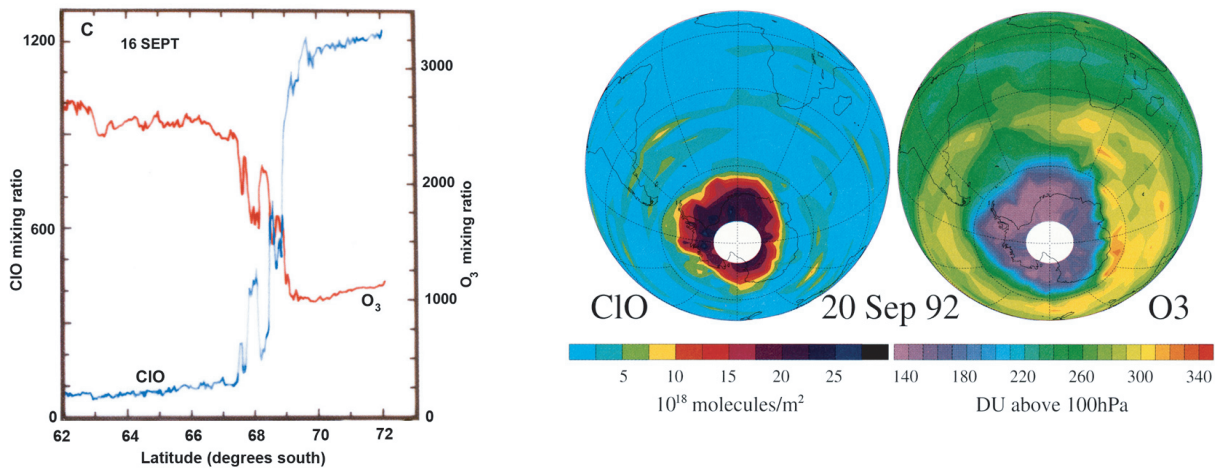


PLATE 2 Ozone-CIO anticorrelation and satellite images of CIO and O<sub>3</sub>. (Left) NASA aircraft in situ CIO-O<sub>3</sub> anticorrelation across Antarctic vortex edge. (Right) NASA microwave LIMB sounder satellite observation of CIO and O<sub>3</sub>. SOURCE: World Meteorological Organization, *Scientific Assessment of Stratospheric Ozone: 1994*, WMO Report 37, Geneva, 1994.

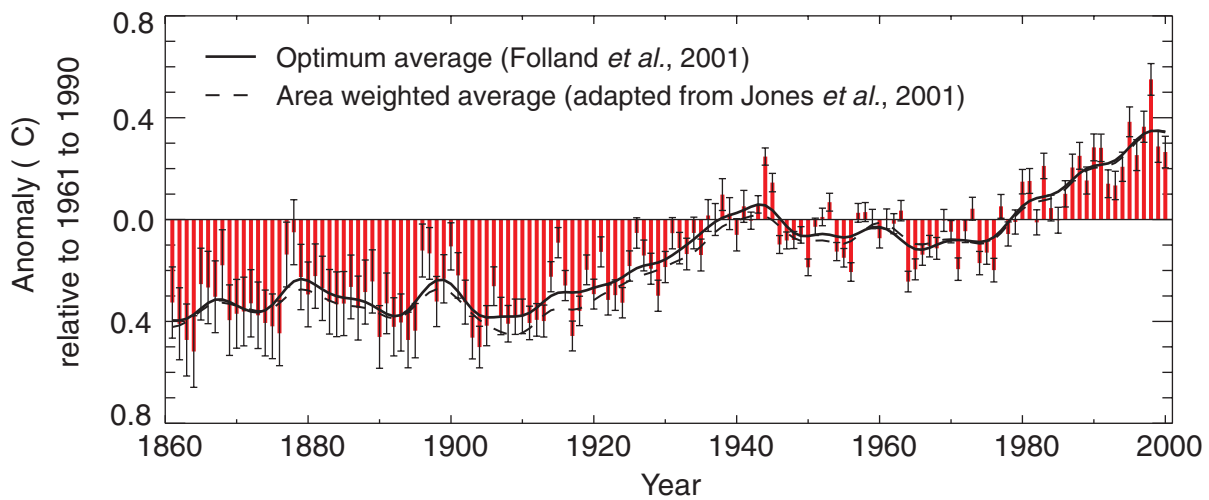


PLATE 3 Annual global land-surface air and sea surface temperature anomalies (°C), 1861 to 2000, relative to 1961 to 1990. Solid curve is the optimally averaged anomalies from Folland et al. [C.K. Folland, N.A. Rayner, S.J. Brown, T.M. Smith, S.S.P. Shen, D.E. Parker, I. Macadam, P.D. Jones, R.N. Jones, N. Nicholls, and D.M.H. Sexton, "Global Temperature Change and Its Uncertainties Since 1861," *Geophys. Res. Lett.* 28(13): 2621-2624, 2001], and the dashed curve is the standard area weighted anomalies (adapted from Jones et al. [P.D. Jones, T.J. Osborn, K.R. Briffa, C.K. Folland, E.B. Horton, L.V. Alexander, D.E. Parker, and N.A. Rayner, "Adjusting for Sampling Density in Grid Box Land and Ocean Surface Temperature Time Series," *J. Geophys. Res.* 106: 3371-3380, 2001]). Unsmoothed optimum averages appear as red bars, and twice their standard errors are denoted by black "I". SOURCE: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001. Reprinted with permission.