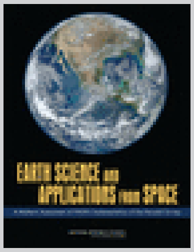

Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey

ISBN
978-0-309-25702-2

124 pages
8 1/2 x 11
PAPERBACK (2012)

Committee on the Assessment of NASA's Earth Science Program; Space Studies Board; Division on Engineering and Physical Sciences; National Research Council

EARTH SCIENCE AND APPLICATIONS FROM SPACE

A Midterm Assessment of NASA's Implementation of the Decadal Survey

Committee on the Assessment of NASA's Earth Science Program

Space Studies Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

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Support for this project was provided by Contract NNH06CE15B between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the agency that provided support for the project.

International Standard Book Number-13: 978-0-309-25702-2
International Standard Book Number-10: 0-309-25702-6

Cover: "Blue Marble" images of the Western Hemisphere (*front cover*) and Eastern Hemisphere (*back cover*) of Earth taken from the Visible/Infrared Imager Radiometer Suite (VIIRS) instrument aboard NASA's recently launched Earth-observing satellite, the Suomi National Polar-orbiting Partnership (NPP). These composite images use a number of swaths of the Earth's surface taken on January 4, 2012. VIIRS is the primary imaging instrument onboard NPP, and it acquires data in 22 spectral bands covering visible, near-infrared, and thermal infrared regions of the electromagnetic spectrum. Images courtesy of NASA/NOAA.

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Preface

Natural and human-induced changes in Earth's interior, land surface, biosphere, atmosphere, and oceans affect all aspects of life. Understanding these changes and their implications requires a foundation of integrated observations—taken from land-, sea-, air-, and space-based platforms—on which to build credible information products, forecast models, and other tools for making informed decisions.

In 2004, the National Research Council (NRC) received requests from NASA's Earth Science Division, the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite Data and Information Service (NESDIS), and the U.S. Geological Survey (USGS) Geography Division to conduct a first in its field "decadal survey" that would generate consensus recommendations from the Earth and environmental science and applications communities regarding a systems approach to the space-based and ancillary observations comprised by the research programs of NASA; the related operational programs of NOAA; and associated programs such as Landsat, a joint initiative of the USGS and NASA.

In carrying out the 2007 Earth science and applications from space decadal survey, participants endeavored to set a new agenda for Earth observations from space in which ensuring practical benefits for humankind plays a role equal to that of acquiring new knowledge about Earth. Those benefits range from information for short-term needs, such as weather forecasts and warnings for protection of life and property, to the longer-term scientific understanding necessary for future applications that will benefit society in ways still to be realized. *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*[1] and *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*[2] were the interim and final reports, respectively, that resulted from this effort.

The 2007 decadal survey called for a set of missions and supporting activities that would advance

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[1]National Research Council, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation,* The National Academies Press, Washington, D.C., 2005.

[2]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

scientific understanding of key processes in the Earth system and provide information to enhance the management of natural resources, including, for example, improvement in early warnings and other responses to threats posed by natural hazards. Recommendations were directed to NASA, NOAA, and the USGS.

In late 2010, NASA requested that the NRC create an ad hoc committee to review the alignment of NASA's Earth Science Division's program with previous NRC advice, primarily that offered in the decadal survey's 2007 final report, *Earth Science and Applications from Space*.[3] The agency was responding to a provision in Section 301(a) of the 2005 NASA Authorization Act requiring that "the performance of each division in the Science directorate of NASA shall be reviewed and assessed by the National Academy of Sciences at 5-year intervals." The resulting ad hoc Committee on the Assessment of NASA's Earth Science Program was asked to assess the following (see Appendix A for the statement of task):

1. How well NASA's current program addresses the strategies, goals, and priorities outlined in the 2007 decadal survey and other relevant NRC reports;
2. Progress toward realizing these strategies, goals, and priorities; and
3. In the context of current and forecast resources, any actions that could be taken to optimize the science value of the program.

The committee was asked not to revisit or alter the science priorities or mission recommendations in the 2007 decadal survey and related NRC reports. However, the committee was invited to provide guidance about implementing the recommended mission portfolio in preparation for the next decadal survey.

The committee met in Washington, D.C., on April 27-29, 2011; in Seattle, Washington, on July 6-8, 2011; and in Irvine, California, on September 21-23, 2011, to gather information and to develop its response to the study charge. Over the course of its meetings, the committee received briefings from Mary Kicza (NOAA), Bruce Quirk (USGS), Michael Freilich (NASA Headquarters), Waleed Abdalati (NASA Headquarters), Rod Heelis and Stephen Fuselier (former co-chairs of the NRC committee for a midterm assessment of NASA's heliophysics program), Byron Tapley (University of Texas, Austin; chair, NASA Advisory Committee Earth Science Subcommittee), Graeme Stephens (Jet Propulsion Laboratory), and Bruce Wielicki (NASA Langley Research Center). The committee also received background documents from other agency officials, including Lawrence Friedl (NASA Headquarters). During the intervals between meetings, the committee had regular teleconferences and extensive electronic communications.

Chapter 1 provides background on the 2007 Earth science and applications from space decadal survey, NASA's Earth science program, and the types of Earth science conducted by NASA, as well as an overview of the benefits society reaps from NASA's Earth science program. Chapter 2 provides an assessment of the major program elements in NASA's Earth science program. Chapter 3 summarizes the primary challenges facing NASA's Earth science program, and it suggests remedies. Chapter 4 provides findings and recommendations to optimize the science value of the program. Chapter 5 identifies lessons learned from the 2007 decadal survey and from the present committee's assessment of NASA's current Earth science program, and it describes how these lessons can be applied to future reviews akin to the decadal survey.

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[3]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007.

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 Report Review Committee of the National Research Council (NRC). 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 review of this report:

Susan K. Avery, Woods Hole Oceanographic Institution,
Inez Y. Fung, University of California, Berkeley,
Charles F. Kennel, University of California, San Diego, Scripps Institution of Oceanography,
Michael D. King, University of Colorado, Boulder,
Steven R. Nerem, University of Colorado, Boulder,
David T. Sandwell, University of California, San Diego, Scripps Institution of Oceanography,
David L. Skole, Michigan State University,
Kevin E. Trenberth, National Center for Atmospheric Research, and
Carl Wunsch, Massachusetts Institute of Technology.

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 Elisabeth M. Drake, Massachusetts Institute of Technology. Appointed by the NRC, she was 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

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 challenges for society as it seeks to achieve prosperity, health, and sustainability.[1]

The 2007 National Research Council report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (referred to in this report as the "2007 decadal survey" or "2007 survey") called for a renewal of the national commitment to a program of Earth observations in which attention to securing practical benefits for humankind plays an equal role with the quest to acquire new knowledge about the Earth system.[2] The decadal survey recommended a balanced interdisciplinary program that would observe the atmosphere, oceans, terrestrial biosphere, and solid Earth and the interactions between these Earth system components to advance understanding of how the system functions for the benefit of both science and society.

NASA responded positively to the decadal survey and its recommendations and began implementing most of them immediately after the survey's release. Although its budgets have never risen to the levels assumed in the survey, NASA's Earth Science Division (ESD) has made major investments toward the missions recommended by the survey and has realized important technological and scientific progress as a result. Several of the survey missions have made significant advances, and operations and applications end users are better integrated into the mission teams. The new Earth Venture competitive solicitation program has initiated five airborne missions and is currently reviewing proposals submitted in response to an orbital stand-alone mission solicitation. At the same time, the Earth sciences have advanced significantly because of existing observational capabilities and the fruit of past investments, along with advances in data and information systems, computer science, and enabling technologies. Three missions already in development

[1]From National Research Council, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation,* The National Academies Press, Washington, D.C., 2005, p. 1.

[2]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

prior to the decadal survey—the Ocean Surface Topography Mission (OSTM), Aquarius, and the Suomi National Polar-orbiting Partnership (NPP)[3]—have since been successfully launched and promise significant benefits to research and applications. The potential for the science community to make use of space-based data for research and applications has never been greater.

> **Finding:** NASA responded favorably and aggressively to the 2007 decadal survey, embracing its overall recommendations for Earth observations, missions, technology investments, and priorities for the underlying science. As a consequence, the science and applications communities have made significant progress over the past 5 years.

However, the Committee on Assessment of NASA's Earth Science Program found that, for several reasons, the survey vision is being realized at a far slower pace than was recommended. Although NASA accepted and began implementing the survey's recommendations, the required budget assumed by the survey was not achieved, greatly slowing implementation of the recommended program. Launch failures, delays, changes in scope, and growth in cost estimates have further hampered the program. In addition, the National Oceanic and Atmospheric Administration (NOAA) has significantly reduced the scope of the nation's future operational environmental satellite series, omitting observational capabilities assumed by the decadal survey to be part of NOAA's future capability and failing to implement the three new missions recommended for NOAA implementation by the survey (the Operational GPS Radio Occultation Mission, the Extended Ocean Vector Winds Mission, and the NOAA portion of CLARREO).

Thus, despite recent and notable successes, such as the launches of OSTM, Aquarius, and Suomi NPP, the nation's Earth observing capability from space is beginning to wane as older missions fail and are not replaced with sufficient cadence to prevent an overall net decline. Using agency estimates for the anticipated remaining lifetime of in-orbit missions and counting new missions formally approved in their enacted budgets, the committee found that the resulting number of NASA and NOAA Earth observing instruments in space by 2020 could be as little as 25 percent of the current number (Figure S.1).[4] This precipitous decline in the quantity of Earth science and applications observations from space undertaken by the United States reinforces the conclusion in the 2007 decadal survey and its predecessor, the 2005 interim report, which declared that the U.S. system of environmental satellites is at risk of collapse.[5] The committee found that a rapid decline in capability is now beginning and that the needs for both investment and careful stewardship of the U.S. Earth observations enterprise are more certain and more urgent now than they were 5 years ago.

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[3]On January 24, 2012, NASA's National Polar-orbiting Operational Environmental Satellite System Preparatory Project, launched on October 28, 2011, was renamed the Suomi National Polar-orbiting Partnership in honor of the late Verner E. Suomi, a renowned meteorologist from the University of Wisconsin considered by many to be "the father of satellite meteorology." See http://www.nasa.gov/mission_pages/NPP/news/suomi.html.

[4]Figure S.1 is an updated version of a similar chart produced by the 2007 decadal survey. Using agency estimates for the anticipated remaining lifetime of in-orbit missions and counting new missions only if they have been formally approved in enacted agency budgets, Figure S.1 indicates that the number of missions could decline from 23 in 2012 to only 6 in 2020, and the number of NASA and NOAA Earth-observing instruments in space could decline from a peak of about 110 in 2011 to approximately 20 in 2020. A more optimistic scenario based on the Climate-Centric Architecture put forth to leverage anticipated augmented funding to support administration priorities is also shown in Figure S.1; however, this plan, which has not been fully funded, also projects a precipitous decline in observing capabilities.

[5]National Research Council, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation,* 2005.

Finding: The nation's Earth observing system is beginning a rapid decline in capability as long-running missions end and key new missions are delayed, lost, or canceled.

The projected loss of observing capability could have significant adverse consequences for science and society. The loss of observations of key Earth system components and processes will weaken the ability to understand and forecast changes arising from interactions and feedbacks within the Earth system and limit the data and information available to users and decision makers. Consequences are likely to include slowing or even reversal of the steady gains in weather forecast accuracy over many years and degradation of the ability to assess and respond to natural hazards and to measure and understand changes in Earth's climate and life support systems. The decrease in capability by 2020 will also have far-reaching consequences for the vigor and breadth of the nation's space-observing industrial and academic base, endangering the pipeline of Earth science and aerospace engineering students and the health of the future workforce.

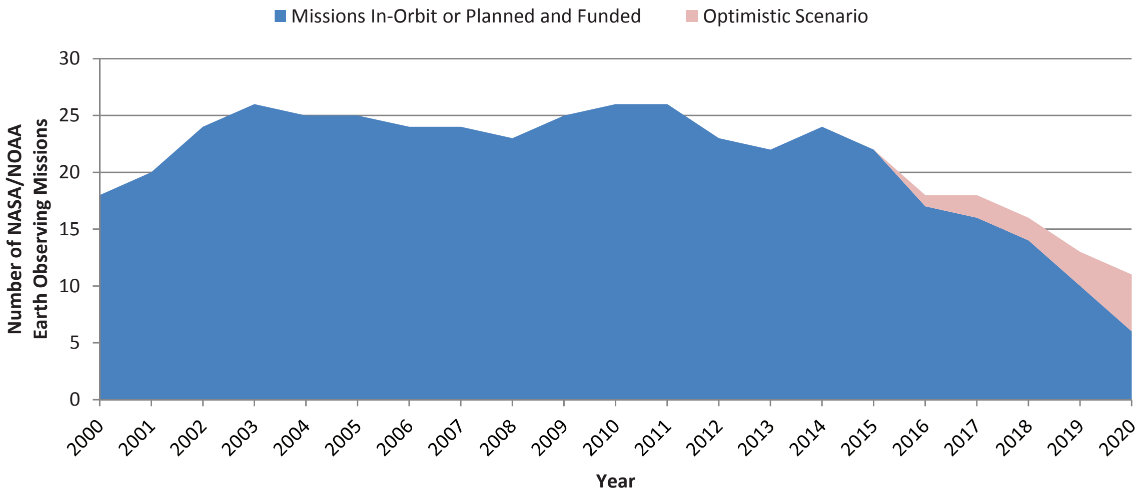
CHALLENGES TO IMPLEMENTATION AND OPPORTUNITIES TO IMPROVE ALIGNMENT WITH THE DECADAL SURVEY

Although there have been a number of successes, NASA's Earth science program has suffered multiple setbacks and other external pressures that are, in many cases, beyond the control of program management. Foremost among these is a budget profile that is not sufficient to execute the 2007 decadal survey's recommended program. In addition, some of the survey-recommended missions have proved more challenging than anticipated, and others envisioned synergies that are not readily achieved via the suggested implementation. The ESD budget has been further strained as a result of mandates from Congress (e.g., the addition of the approximately $150 million TIRS [Thermal Infrared Sensor] to the Landsat Data Continuity Mission) and the interjection of administration priorities (e.g., the Climate Continuity missions[6]) without the commensurate required funding.

Finding: Funding for NASA's Earth science program has not been restored to the $2 billion per year (in fiscal year [FY] 2006 dollars) level needed to execute the 2007 decadal survey's recommended program. Congress's failure to restore the Earth science budget to a $2 billion level is a principal reason for NASA's inability to realize the mission launch cadence recommended by the survey.

The committee concluded that in the near term, budgets for NASA's Earth science program will remain incommensurate with programmatic needs. However, even as NASA strives to "do more with less," it is confronted with challenges, including limited access to affordable medium-class launch vehicles—the mainstay of Earth observation programs—and significant growth in the cost to develop instruments and spacecraft, a consequence, in part, of how NASA manages its space missions. These challenges (discussed further in Chapter 3) have hindered implementation of the envisioned balanced Earth system science program. With respect to cost growth, the committee found that decadal survey missions have thus far not been managed with sufficient consideration of the scope and cost outlined in the 2007 decadal survey in either an absolute or a relative sense. Chapter 4 offers recommendations to establish and manage mission costs.

[6]NASA, "Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space," June 2010. Available at http://science.nasa.gov/media/medialibrary/2010/07/01/Climate_Architecture_Final.pdf.



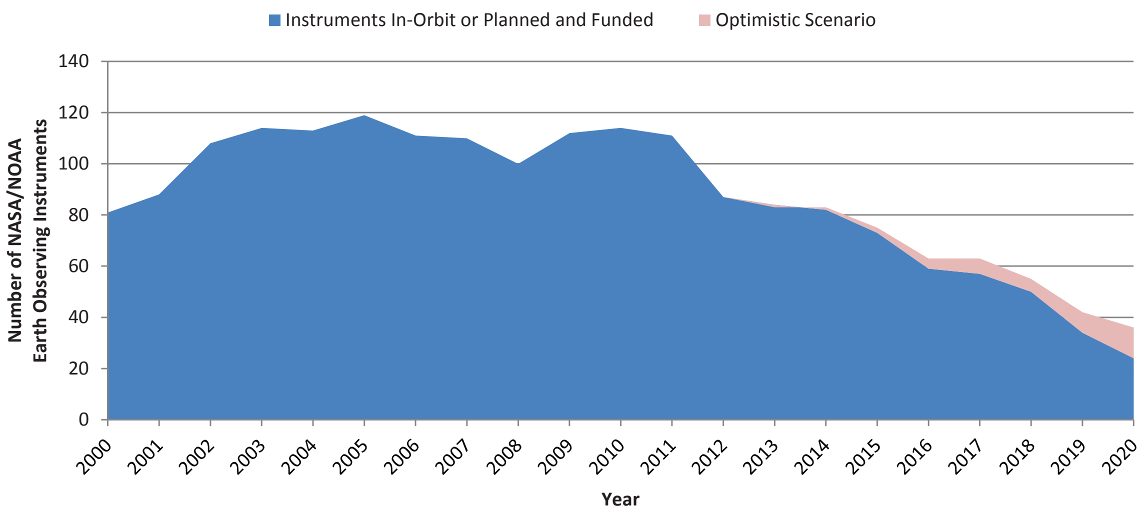


FIGURE S.1 Number of operating (2000-2011) and planned (2012-2020) NASA and NOAA Earth observing missions (*top*) and instruments (*bottom*). Shown in blue are missions that are funded and have a specified launch date in NASA or NOAA budget submissions. Thus, the blue curve does not count missions (and associated instruments) that have been proposed or planned but are not yet funded or selected. Shown in pink is an "optimistic scenario" based on the Climate-Centric Architecture put forth to leverage anticipated augmented funding to support administration priorities that makes the following assumptions: GRACE-FO launches in 2016, PACE launches in 2019, ASCENDS launches in 2020, SWOT launches in 2020, EV-2 launches in 2017, SAGE-3 instrument launches in 2014, OCO-3 instrument launches in 2015, and EV-I instruments are launched every year starting in 2017 (plans are for EV-I instruments to be delivered for integration yearly; this assumes they also launch yearly). NOTE: Mission lifetimes for on-orbit missions are taken from estimates provided by NASA and NOAA; the NASA estimates are based on mission team estimates of remaining mission lifetime as provided (and reviewed by the Technical Panel) during the Senior Review process. Acronyms are defined in Appendix G. SOURCE: NASA and NOAA data.

Recommendation:

- **NASA's Earth Science Division (ESD) should implement its missions via a cost-constrained approach, requiring that cost partially or fully constrain the scope of each mission such that realistic science and applications objectives can be accomplished within a reasonable and achievable future budget scenario.**

Further, recognizing that survey-derived cost estimates are by necessity very approximate and that subsequent, more detailed analyses may determine that all of the desired science objectives of a particular mission cannot be achieved at the estimated cost,

- **NASA's ESD should interpret the 2007 decadal survey's estimates of mission costs as an expression of the relative level of investment that the survey's authoring committee believed appropriate to advance the intended science and should apportion funds accordingly, even if all desired science objectives for the mission might not be achieved.**

To coordinate decisions regarding mission technical capabilities, cost, and schedule in the context of overarching Earth system science and applications objectives, the committee also recommends that

- **NASA's ESD should establish a cross-mission Earth system science and engineering team to advise NASA on execution of the broad suite of decadal survey missions within the interdisciplinary context advocated by the 2007 decadal survey. The advisory team would assist NASA in coordinating decisions regarding mission technical capabilities, cost, and schedule in the context of overarching Earth system science and applications objectives.**[7,8]

The cost of executing survey-recommended missions has increased, in part because of the lack of availability of a medium-class launch vehicle. To control costs and to optimize the use of scarce fiscal resources, the 2007 decadal survey recommended mostly small- and medium-class missions that could utilize relatively low-cost small- or medium-class launch vehicles (e.g., Pegasus, Taurus, and Delta II). However, the Taurus launch vehicle has failed in its past two launches, and the Delta II is being phased out as the commercial sector focuses on heavier-lift launch vehicles, which are substantially more expensive to procure. Use of such heavy-lift launch vehicles is not generally cost-effective for Earth science missions; indeed, the excess capability and high cost of these vehicles encourage designers to grow their payloads to better match the launcher's capabilities, which encourages growth in scope and cost. The lack of a reliable and low-cost medium-capability launch vehicle thus directly threatens programmatic robustness. The committee offers the following finding and recommendation concerning the cost and availability of medium-class launch vehicles (see the section "Access to Space" in Chapter 3):

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[7]The team, similar to the Payload Advisory Panel established by NASA to assist in implementation of its Earth Observing System (EOS), would draw its membership from the scientists and engineers involved in the definition and execution of survey missions as well as the nation's scientific and engineering talent more broadly. (The Payload Advisory Panel was composed of the EOS Interdisciplinary Science Investigation principal investigators and was formally charged with examining and recommending EOS payloads to NASA based on the scientific requirements and priorities established by the Earth science community at large. See NASA, *Earth Observing System (EOS) Reference Handbook,* G. Asrar and D.J. Dokken, eds., Earth Science Support Office, Document Resource Facility, Washington, D.C., 1993.)

[8]The committee believes that NASA is best positioned to determine whether this advisory panel should be constituted as a Federal Advisory Committee Act-compliant advisory body.

Finding: Lack of reliable, affordable, and predictable access to space has become a key impediment to implementing NASA's Earth science program. Furthermore, the lack of a medium-class launch vehicle threatens programmatic robustness.

Recommendation: NASA should seek to ensure the availability of a highly reliable, affordable medium-class launch capability.

Another impediment to effective and efficient implementation of the 2007 decadal survey is the lack of a national strategy for establishment and management of Earth observations from space. This problem was recognized in the decadal survey report, which stated (as quoted in this midterm assessment report),

> The committee is concerned that the nation's institutions involved in civil Earth science and applications from space (including NASA, NOAA, and USGS) are not adequately prepared to meet society's rapidly evolving Earth information needs. Those institutions have responsibilities that are in many cases mismatched with their authorities and resources: institutional mandates are inconsistent with agency charters, budgets are not well matched to emerging needs, and shared responsibilities are supported inconsistently by mechanisms for cooperation. These are issues whose solutions will require action at high levels of the federal government.[9]

Such a strategy is perhaps even more important in an era of severe fiscal constraint. Not only is such a strategy important for optimizing NASA's and the nation's resources dedicated to Earth system science, but also it is critical to meeting national needs for the results of Earth system science, including the understanding of climate change and land use. The decadal survey recommended that "the Office of Science and Technology Policy, in collaboration with the relevant agencies and in consultation with the scientific community, should develop and implement a plan for achieving and sustaining global Earth observations. This plan should recognize the complexity of differing agency roles, responsibilities, and capabilities as well as the lessons from the implementation of the Landsat, EOS, and NPOESS programs."[10,11]

Despite this and other subsequent calls from the community for this national strategy, only a preliminary plan has been outlined.[12] A more complete plan for achieving and sustaining global Earth observations remains to be presented or funded. However, the recently released NASA Climate-Centric Architecture plan[13] includes a set of Climate Continuity missions, tacitly recognizing for the first time NASA's role in sustained observations associated with climate (see the section "Lack of a National Strategy for Establishment and Management of Earth Observations from Space" in Chapter 3).

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[9]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 61.

[10]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 14.

[11]Following a major restructuring in 2010, the joint NOAA-Air Force procurement of the polar-orbiting satellite system called NPOESS was ended. The NOAA portion of the NPOESS program is now the Joint Polar Satellite System (JPSS). See, U.S. House of Representatives, "From NPOESS to JPSS: An Update on the Nationís Restructured Polar Weather Satellite System," Hearing Charter, Committee on Science, Space and Technology, Subcommittee on Investigations and Oversight and the Subcommittee on Energy and Environment, September 23, 2011, available at http://science.house.gov/hearing/joint-hearing-investigations-and-oversight-energy-and-environment-subcommittees-polar.

[12]See "Achieving and Sustaining Earth Observations: A Preliminary Plan Based on a Strategic Assessment by the US Group on Earth Observations," Office of Science and Technology Policy, September 2010, available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp-usgeo-report-earth-obs.pdf (accessed November 2011).

[13]NASA, "Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space," available at http://science.nasa.gov/media/medialibrary/2010/07/01/Climate_Architecture_Final.pdf.

Finding: The 2007 decadal survey's recommendation that the Office of Science and Technology Policy develop an interagency framework for a sustained global Earth observing system has not been implemented. The committee concluded that the lack of such an implementable and funded strategy has become a key, but not the sole, impediment to sustaining Earth science and applications from space.

Chapter 4 discusses a number of items that should be considered in the formulation of such a national strategy.

In addition to cost control measures, the committee considered other ways for ESD to maximize the value of its limited resources. These include the possible augmentation of the Earth Venture-class program discussed below, and use of alternative and/or synergistic platforms or novel flight architectures (including suborbital platforms as previously mentioned), as well as seeking value-added international partnerships. Alternative platforms such as balloons and aircraft (piloted and unpiloted), hosted payloads, small satellites, the International Space Station, and flight formations (for example, the Afternoon Constellation, or "A-Train") provide NASA with a diverse portfolio of options for exploring different and, where appropriate, less costly ways of conducting Earth observations and measurements (see the section "Alternative Platforms and Flight Formations" in Chapter 4).

Finding: Alternative platforms and flight formations offer programmatic flexibility. In some cases, they may be employed to lower the cost of meeting science objectives and/or maturing remote sensing and in situ observing technologies.

Large uncertainties are typical when attempting to factor international partner missions into long-term plans for U.S. Earth observation missions. Nevertheless, the committee found that ESD has made admirable efforts in securing such partnerships (see the section "International Partnerships" in Chapter 4).

Finding: NASA has made considerable efforts to secure international partnerships to meet its science goals and operational requirements.

STATUS OF PROGRAM ELEMENTS IN NASA'S EARTH SCIENCE PROGRAM

In its assessment of NASA's Earth science program, the committee examined the major individual programmatic elements within NASA's ESD and also considered the overall program's effectiveness in realizing the objectives of the 2007 decadal survey.[14] In particular, the committee reviewed the following program elements and also commented on NASA's Climate Continuity missions. The program elements described in this summary are elaborated on in Chapter 2, where they are listed in the same order as they are here:

- Extended missions—missions whose operations have been extended beyond their nominal lifetime;
- Missions in the pre-decadal survey queue—missions that the decadal survey assumed would be launched as precursors to the decadal survey missions;
- Decadal survey missions—new missions recommended by the 2007 decadal survey;
- Climate Continuity missions;
- Earth Venture missions—a class of smaller missions recommended by the decadal survey;
- Applied Sciences Program;

[14]A full listing of all the findings and recommendations in the 2007 decadal survey, as well as responses to each of those from NASA in 2009 and updated responses presented to the committee in April 2011, is available in Appendix E.

- Suborbital (Earth Science) Program;
- Technology development; and
- Research and analysis.

Extended Missions

Extended missions (missions that operate and provide data beyond their originally planned and funded mission lifetimes) continue to provide a wealth of observations and measurements of benefit to society and to the Earth science community. Data from extended missions are critical to the operations of users such as NOAA's National Weather Service; they also provide information of fundamental importance to advance Earth science research. Overall, the committee strongly supports the process of the NASA Earth Science Senior Review that evaluates these missions and makes recommendations concerning their funding and continuation.

Missions in the Pre-Decadal Survey Queue

The committee supports NASA's efforts to fly out its pre-decadal survey mission queue, also referred to as "foundational" missions. Unfortunately, delays, changes in scope, and launch failures[15] have hindered progress in implementing the pre-decadal survey mission queue.

Decadal Survey Missions

Implementation of the recommended decadal survey mission queue is proceeding at a pace that is slower than originally envisioned in the survey. Only two of the four Phase 1 missions recommended for implementation by 2013—SMAP and ICESat-2—have entered their implementation phase, while two other missions—DESDynI and CLARREO—remain in pre-Phase A formulation and will likely face significant delays as a result of budget constraints. NOAA, facing its own budget constraints, has requested that NASA assume responsibility for implementing the sea-surface vector winds mission XOVWM (see Table S.1).

Climate Continuity Missions

To balance executive branch and congressional priorities with the community guidance set forth in the decadal survey, the NASA Earth science program issued the report *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space*,[16] which convolves decadal survey and administration priorities to take advantage of new funds made available by the executive branch to accelerate its priorities. Although the committee was encouraged by ESD's incorporation of the priorities of the decadal survey into its 2010 report, the committee is concerned that in a static or shrinking budget environment there is tension between the need to continue successful Earth science measurements and the need for timely implementation of decadal survey missions. This problem is further compounded by the lack of an interagency framework for a sustained global Earth observing system.

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[15]Two important NASA missions—Glory and Orbiting Carbon Observatory (OCO)—were lost because of launch vehicle failures. Lack of reliable, affordable, and predictable access to space has now become a key impediment to implementing NASA's Earth science program.

[16]See http://science.nasa.gov/media/medialibrary/2010/07/01/Climate_Architecture_Final.pdf.

Earth Venture Missions

NASA has moved expeditiously to implement the Earth Venture-class program, a new mission class recommended by the decadal survey.[17] NASA has released two solicitations for the Earth Venture program, one targeted toward suborbital investigations and one for a stand-alone mission that involves relatively simple, small instruments, spacecraft, and launch vehicles. As of December 2011, a draft solicitation had also been released for the first Earth Venture Instruments, targeting principal investigator (PI)-led instrument development. Currently, NASA plans to release Earth Venture stand-alone solicitations every 4 years, suborbital solicitations every 4 years, and instrument of opportunity solicitations every 15-18 months. Earth Venture standalone (space-based) missions further offer an important opportunity to increase the launch frequency of Earth science missions, and thus the committee offers the following finding and recommendation.

Finding: The Earth Venture-class program is being well implemented by NASA and is a crucial component of fulfilling the 2007 decadal survey's objectives.

Recommendation: Consistent with available budgets and a balanced Earth observation program from space based on the 2007 decadal survey recommendations, NASA should consider increasing the frequency of Earth Venture stand-alone/space-based missions.

Applied Sciences Program

The Earth science and applications from space decadal survey establishes a vision acknowledging the dual importance of basic science and applications for societal benefits. With limited resources,[18] the Applied Sciences Program (ASP) within ESD has built a coherent program that is facilitating the use of remote sensing observations for societal benefits, mostly through collaborations with other federal agencies. Other activities include projects to encourage experts in the applications community to participate in specific mission definition teams and workshops. The engagement of end users throughout the entire mission life cycle is necessary to ensure that user needs are well understood; ASP appears to be following this model. ASP efforts appear to be aligned with the spirit and intent of the 2007 decadal survey.

Finding: Aligned with the intent of the 2007 decadal survey, NASA's Applied Sciences Program has begun to engage applied researchers and governmental (federal and state) operational users on some decadal survey mission science definition and applications teams and to conduct research to better understand the value of these applications.

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[17] The decadal survey made the following recommendation, "To restore more frequent launch opportunities and to facilitate the demonstration of innovative ideas and higher-risk technologies, NASA should create a new Venture class of low-cost research and application missions (approximately $100 million to $200 million). These missions should focus on fostering revolutionary innovation and on training future leaders of space-based Earth science and applications." See National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, 2007, p. 59.

[18] Ray Hoff, chair of the NASA Applied Science Advisory Group, cited on p. 8 of "Meeting Minutes," from the October 10, 2010, meeting of the NASA ASAG. Available at http://science.nasa.gov/media/medialibrary/ 2011/01/06/FinalASAGMeetingMinutesOctober 2010-1_TAGGED.pdf.

TABLE S.1 Current Status of Earth Science and Applications Decadal Survey Recommended Missions

Mission	Mission Description (from 2007 decadal survey)	Recommended Launch Time Frame	Planned Launch Date	Status[a]
CLARREO (Climate Absolute Radiance and Refractivity Observatory)	Solar and Earth radiation; spectrally resolved forcing and response of the climate system	2010-2013	None[b]	Formulation (Pre-Phase A)
SMAP (Soil Moisture Active-Passive)	Soil moisture and freeze-thaw for weather and water-cycle processes	2010-2013	November 2014	Implementation Phase (Phase B)
ICESat-II	Ice sheet height changes for climate change diagnosis	2010-2013	October 2015	Implementation Phase (Phase A)
DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice)	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	2010-2013	None[b]	Formulation (Pre-Phase A)
HyspIRI (Hyperspectral Infrared Imager)	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	2013-2016	None	Formulation (Pre-Phase A)
ASCENDS (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons)	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	2013-2016	None[c]	Formulation (Pre-Phase A)
SWOT (Surface Water and Ocean Topography)	Ocean, lake, and river water levels for ocean and inland water dynamics	2013-2016	None[d]	Formulation (Pre-Phase A)
GEO-CAPE (Geostationary Coastal and Air Pollution Events Mission)	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	2013-2016	None	Formulation (Pre-Phase A)
ACE (Aerosol/Cloud/Ecosystems Mission)	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	2013-2016	None	Formulation (Pre-Phase A)
LIST (Lidar Surface Topography)	Land surface topography for landslide hazards and water runoff	2016-2020	None	Formulation (Pre-Phase A)
PATH (Precipitation and All-weather Temperature and Humidity)	High-frequency, all-weather temperature and humidity soundings for weather forecasting and sea-surface temperature[e]	2016-2020	None	Formulation (Pre-Phase A)
GRACE-II (Gravity Recovery and Climate Experiment-II)	High-temporal-resolution gravity fields for tracking large-scale water movement	2016-2020	None[f]	Formulation (Pre-Phase A)
SCLP (Snow and Cold Land Processes)	Snow accumulation for freshwater availability	2016-2020	None	Formulation (Pre-Phase A)
GACM (Global Atmospheric Composition Mission)	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	2016-2020	None	Formulation (Pre-Phase A)
3D-WINDS (Demo) (3D Tropospheric Winds from Space-based Lidar)	Tropospheric winds for weather forecasting and pollution transport	2016-2020	None	Formulation (Pre-Phase A)

[a]During Pre-Phase A, a pre-project team studies a broad range of mission concepts that contribute to program and mission directorate goals and objectives. These advanced studies, along with interactions with customers and other potential stakeholders, help the team to identify promising mission concepts and draft project-level requirements. The team also identifies potential technology needs (based on the best mission concepts) and assesses the gaps between such needs and current and planned technology readiness levels. See NASA NPR 7120.5, available at http://www.hq.nasa.gov/office/codeq/doctree/71205.htm.

During Phase A, a project team is formed to fully develop a baseline mission concept and begin or assume responsibility for the development of needed technologies. This work, along with interactions with customers and other potential stakeholders, helps with the baselining of a mission concept and the program requirements on the project. These activities are focused toward System Requirements Review (SRR) and System Definition Review (SDR/PNAR) (or Mission Definition Review (MDR/PNAR)). See NASA NPR 7120.5, available at http://www.hq.nasa.gov/office/codeq/doctree/71205.htm.

During Phase B, the project team completes its preliminary design and technology development. These activities are focused toward completing the Project Plan and Preliminary Design Review (PDR)/Non-Advocate Review (NAR). See NASA NPR 7120.5, available at http://www.hq.nasa.gov/office/codeq/doctree/71205.htm.

[b]In the 2010 NASA report *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space* (available at http://nasascience.nasa.gov/earth-science/), CLARREO (the first of two mission components) and DESDynI (two spacecraft sharing a single launch vehicle) were slated for launch in 2017. The committee was informed at its first meeting on April 28, 2011, by the director of NASA's Earth Science Division, Michael Freilich, that these plans are now on hold because the fiscal year 2012 budget request does not fund mission implementation; no new target launch dates are available for these missions.

[c]Mission planned for launch by end of 2019 per NASA, *Responding to the Challenge of Climate and Environmental Change* (2010); however, a formal target launch date is not determined until after Mission Concept Review, when a budget wedge is established.

[d]Mission planned for launch by the end of 2020 per NASA, *Responding to the Challenge of Climate and Environmental Change* (2010); however, a formal target launch date is not determined until after Mission Concept Review, when a budget wedge is established.

[e]Cloud-independent, high-temporal-resolution, lower-accuracy sea-surface temperature measurements to complement, not replace, global operational high-accuracy sea-surface temperature measurements.

[f]The GRACE Follow-on Mission, a climate continuity mission called for in NASA's June 2010 climate-centric architecture report, will provide many of the observations envisioned by the 2007 decadal survey for GRACE-II.

Suborbital Program

NASA's suborbital program was in decline for almost a decade, but following the release of the decadal survey in 2007, it has made a significant rebound with almost a doubling of financial support for its airborne program. Total flight hours have increased by a factor of 2.5, and flight hours associated with survey missions have doubled from FY2006 to FY2011. Suborbital platforms serve many purposes, including serving as technology testbeds, enabling instrument flight test and algorithm development before launch, providing data complementary to spaceborne observations, providing for calibration of instruments and algorithm validation measurements post-launch in support of data product generation, and directly contributing to local and regional scientific process studies. In addition, NASA Earth observing missions from the Airborne Science Program support "gap filler" missions, such as Operation Ice Bridge, which acquire observations between satellite missions. The committee's review led to the following finding:

> **Finding:** The suborbital program, and in particular the Airborne Science Program, is highly synergistic with upcoming Earth science satellite missions and is being well implemented. NASA has fulfilled the recommendation of the decadal survey to enhance the program.

Technology Development

Within NASA ESD is the NASA Earth Science Technology Office (ESTO), which is responsible for promoting the development of technology required to make the decadal survey missions flight ready. ESTO has funded more than 70 new, competitively selected projects that support each of the decadal survey missions to varying degrees. Furthermore, the recent ESTO solicitation for advanced information system technologies was partnered with, and partially funded by, ESD's Applied Sciences Program to help ensure the transition into operations of technologically matured information systems through applied science demonstrations and pathfinders. Based on its review, the committee found as follows:

Finding: ESTO has organized its proposal solicitations around the 2007 decadal survey and is investing to advance technological readiness across the survey mission queue.

Research and Analysis

According to NASA, research and analysis (R&A) is "the core of the [Earth Science] research program and funds the analysis and interpretation of data from NASA's satellites, as well as a full range of underlying scientific activity needed to establish a rigorous base for the satellite data and their use in computational models (for both assimilation and forecasting). The complexity of the Earth system, in which spatial and temporal variability exists on a range of scales, requires an organized approach for addressing complex, interdisciplinary problems, taking care to recognize the objective of integrating science across the programmatic elements towards a comprehensive understanding of the Earth system."[19] Recognizing the critical importance of R&A, the decadal survey made the following recommendation to NASA: "NASA should increase support for its research and analysis (R&A) program to a level commensurate with its ongoing and planned missions. Further, in light of the need for a healthy R&A program that is not mission-specific, as well as the need for mission-specific R&A, NASA's space-based missions should have adequate R&A lines within each mission budget as well as mission-specific operations and data analysis. These R&A lines should be protected within the missions and not used simply as mission reserves to cover cost growth on the hardware side."[20]

Through the current R&A program there have been advances in modeling, analysis, and data assimilation, yet much research is still needed to understand the processes in the Earth system and to fully assimilate Earth observations in Earth system models, thereby creating a consistent and integrated picture of Earth. Indeed, the committee emphasizes that a robust R&A program is a necessary condition to achieve the objectives outlined in the 2007 survey. Despite progress made in R&A investments, the challenges facing NASA's entire Earth science program mean that protecting the nation's investments in R&A is as important moving forward as in the past.

Finding: NASA has maintained a healthy investment in R&A activities and has protected the budgets of both mission-specific and non-mission-specific R&A programs against possible reallocation to cover cost growth in mission hardware.

[19]NASA's FY 2012 President's Budget Request: Estimates for Science-Earth Science, p. ES-17. Available at http://www.nasa.gov/pdf/516645main_NASAFY12_Budget_Estimates-Science_Earth-508.pdf.

[20]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, 2007, p. 15.

THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

The committee's assessment of NASA's Earth science program could not be accomplished without also reviewing the state of NOAA's missions and Earth science program. NOAA's current and planned polar and geostationary programs were assumed by the 2007 survey's committee to be an integral part of the baseline capabilities as it developed its integrated strategy. Two of the survey's recommended 17 missions (the Operational GPS Radio Occultation Mission and the Extended Ocean Vector Winds Mission) and part of a third (CLARREO) were directed for implementation by NOAA, but none has been implemented. This committee offers the following finding on NOAA's implementation of recommendations to the agency from the 2007 decadal survey:

> **Finding:** NOAA's capability to implement the assumed baseline and the recommended program of the 2007 decadal survey has been greatly diminished by budget shortfalls; cost overruns and delays, especially those associated with the NPOESS program prior to its restructuring in 2010 to become the Joint Polar Satellite System (JPSS); and by sensor descopes and sensor eliminations on both NPOESS and GOES-R.[21]

These descopes impacted numerous ESD science communities. The committee notes that in an era of budget austerity, NASA's ESD has very limited capabilities to mitigate the effect of these shortfalls.

LOOKING AHEAD: BEYOND 2020

In preparation for the next decadal survey, the committee offers in Chapter 5 a summary of "lessons learned" that are derived from its evaluation of implementation of the current decadal survey programs. In particular, regardless of how future NASA Earth science programs evolve, the committee concluded that:

1. Maintaining a long-term vision with a fixed and predictable mission queue is essential to building a consensus in a diverse Earth science community that prior to the 2007 decadal survey had not come to a consensus on research priorities spanning conventional disciplinary boundaries. The strength of the decadal survey and its value to agencies and decision makers are, in fact, the consensus priorities established by the survey's outreach and deliberative processes. Without community "buy-in" to the survey, a return to an ad hoc decision process that is less informed and less efficient in its allocation of resources is the default to be expected.
2. Finding the balance between prioritizing science objectives and creating a mission queue that is viable will be one of the great challenges for the Earth science community over the coming decades. Too much focus on either risks the long-term sustainability and value of NASA's Earth science program.

[21]Even before the latest round of budget-driven delays and descopes, NOAA polar and geostationary programs had experienced severe budget challenges with particular consequences for research and operations deemed outside required "core" capabilities. See National Research Council, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring,* The National Academies Press, Washington, D.C., 2008. The Government Accountability Office (GAO) has published a number of reports detailing the origins of the cost overruns and assessing program management. See, for example, GAO, *Polar-orbiting Environmental Satellites: Agencies Must Act Quickly to Address Risks That Jeopardize the Continuity of Weather and Climate Data,* GAO-10-558 (Washington, D.C., May 10, 2010) and *Polar-orbiting Environmental Satellites: With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making,* GAO-09-564 (Washington, D.C., June 17, 2009).

3. The community will need to give more thought to balancing costs with science objectives and priorities. More explicit decision rules for different budget contingencies might also prove helpful for program managers.

4. Finally, the community will have to look at different ways to construct a healthy and robust mission portfolio—for example, through partnerships and alternative platforms in addition to individual spacecraft and suborbital missions. Preparatory work to identify new technologies and readiness levels could be done ahead of any formal review and indeed could serve as an input to such a review.

1

The Decadal Survey Vision

NASA'S EARTH SCIENCE PROGRAM

The Earth Science Division (ESD) at NASA is organized within the agency's Science Mission Directorate (SMD), whose programs seek to answer the following questions:

1. How and why are Earth's climate and the environment changing?
2. How and why does the Sun vary and affect Earth and the rest of the solar system?
3. How do planets and life originate?
4. How does the universe work, and what are its origin and destiny?
5. Are we alone?

The first four of these top-level questions inform the activities of SMD's Earth Science, Heliophysics, Planetary Science, and Astrophysics divisions, respectively, while the fifth refers to a cross-division program in astrobiology. Another variant of the top-level objectives of the Earth science program—one that emphasizes the centrality of "Earth system science"[1]—appears on the SMD website, where it is stated, "The purpose of NASA's Earth science program is to develop a scientific understanding of Earth's system and its response to natural or human-induced changes, and to improve prediction of climate, weather, and natural hazards."[2]

In developing its overall strategy and implementation plan, ESD draws extensively from the guidance provided in the National Research Council's (NRC's) 2007 report *Earth Science and Applications from*

[1]The origins of "Earth system science" at NASA are associated with the creation in 1983 by the NASA Advisory Council of an Earth System Sciences Committee, which was chaired by Francis Bretherton. A 1986 report from that committee states "The goal of Earth system science is to obtain a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all timescales." (Earth System Science Committee, *Earth System Science: A Program for Global Change,* Washington D.C., 1986, p. 26.)

[2]NASA, "NASA Science: Earth," available at http://science.nasa.gov/earth-science/.

Space: National Imperatives for the Next Decade and Beyond.[3] Indeed, in ESD's portion of the SMD 2010 Science Plan, the connection between the objectives of the division and the decadal survey's "vision" is explicit:[4]

> At NASA's request, the National Research Council conducted the first ever Decadal Survey for Earth Science, and released in 2007 the report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. In it, the NRC articulates the following vision for the future:
>
> > *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 challenges for society as it seeks to achieve prosperity, health, and sustainability.*
>
> NASA's ability to observe our changing planet from the vantage point of space and use these observations to advance understanding and to support applications that support society is essential to realizing this vision.

The 2007 decadal survey outlined the components of an Earth information system to address recognized national needs for Earth system research and applications to benefit society.[5] It also described an observational portion of a strategy for obtaining an integrated set of space-based measurements essential to such a system over the period from 2010 to 2020.[6] Although they are but one part of the requisite Earth information system, space-based measurements provide unique and key data for analyzing Earth as a global system of interconnected human activities and natural processes.

With its emphasis on advancement of Earth system science, the SMD science strategy is well aligned with that expressed in the survey. In particular, the SMD 2010 Science Plan states,[7]

> NASA's strategic goal: "Advance Earth System Science to meet the challenges of climate and environmental change" is expressed by the fundamental question, "How is the Earth changing and what are the consequences for life on Earth?" and its component questions:
>
> - How is the global Earth system changing? *(Characterize)*
> - What are the sources of change in the Earth system and their magnitudes and trends? *(Understand)*
> - How will the Earth system change in the future? *(Predict)*
> - How can Earth system science improve mitigation of an adaptation to global change? *(Apply)*

The alignment of NASA's objectives for its Earth science program and that articulated by the survey is also recognized in the present study's statement of task, where it is stated that "the National Research Council shall convene an ad hoc committee to review the alignment of NASA's Earth Science Division's program with previous NRC advice, primarily the 2007 NRC decadal survey report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond"* (see Appendix A).

In summary, for purposes of the present study, an evaluation of NASA's Earth science program is effectively an assessment of progress toward achieving the objectives of the decadal survey.

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[3]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

[4]NASA, *2010 Science Plan for NASA's Science Mission Directorate,* NASA Headquarters, Washington, D.C., July 2010, p. 24.

[5]See Chapter 1, "An Integrated Strategy for Earth Science and Applications from Space," pp. 17-26 in National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007.

[6]See Chapter 2, "The Next Decade of Earth Observations from Space," pp. 27-60 in National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007.

[7]NASA, *2010 Science Plan for NASA's Science Mission Directorate,* July 2010, pp. 24-25.

EARTH SCIENCE AND APPLICATIONS FROM SPACE

The decadal survey's vision for the future, stated above, was first enunciated in the 2005 interim report of the survey.[8] It was subsequently reaffirmed in the survey's 2007 final report and is highlighted in NASA's 2010 Science Plan.[9] It calls for a program of Earth science research and applications in support of society—one that includes advances in fundamental understanding of the Earth system and increased application of this understanding to serve the nation and the people of the world. Indeed, the decadal survey was emphatic in its recommendation for a renewal of the national commitment to a program of Earth observations in which attention to securing practical benefits for humankind plays an equal role with the quest to acquire new knowledge about the Earth system. These societal benefits[10] are critical to a growing and more complex society that is increasingly vulnerable to natural and human-induced changes. The present committee endorses this view and finds that understanding Earth as a system will continue to be a critical scientific goal.

Earth System Science

The various components of the Earth system are so interconnected and interdependent that advances in understanding one component of the Earth system may require scientific progress across disciplines. In contrast to other observational programs at NASA, acquisition of the data needed to enable advances in understanding the Earth system—"Earth system science"[11]—requires a broad range of active and passive measurements from space, airborne, and in situ platforms and over very broad spatial and temporal scales. Furthermore, the relationship between understanding Earth as a system and the decisions that societies make to achieve prosperity and sustainability likewise is critical in a world in which the population and the consumption of resources continue to grow, vulnerability to weather and natural hazards (Figure 1.1) is increasing, the need for more effective management of natural resources is evident, and aspirations for better quality of life remain only partially fulfilled. Earth observations from space and advances in Earth system science are thus of ever-increasing importance to the nation—they enable accurate weather forecasts and warnings (Box 1.1), support fact-based decision making (e.g., in relation to fire-threat level, forest fire detection, space weather alerts and predictions of geomagnetic storm impacts such as radio blackouts, and volcanic ash tracking for aviation safety), inform policy (e.g., world agricultural production assessments by the U.S. Department of Agriculture's Foreign Agricultural Service),[12] and have the potential to deliver profound societal and economic benefits to the nation.

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[8]National Research Council, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation,* The National Academies Press, Washington, D.C., 2005.

[9]NASA, *2010 Science Plan for NASA's Science Mission Directorate,* July 2010.

[10]Earth observations from space are the foundation for weather forecasts and warnings and for wise decision making to support management and operations in a variety of societal sectors, including energy, transportation, water, agriculture, and national defense.

[11]Earth system science involves the observation, understanding, and protection of the five interconnected components of the system: (1) the atmosphere, (2) the hydrosphere (the oceans and all water on Earth), (3) the cryosphere (all ice and snow), (4) the lithosphere (the ever-changing Earth's crust and mantle), and (5) the biosphere (with its rich diversity of life including more than 7 billion humans). The social and economic welfare of the entire human population is dependent on this interconnected Earth system for its food, water, energy, health, and quality of life.

[12]U.S. Department of Agriculture, Foreign Agricultural Service, *World Agricultural Production,* Circular Series WAP 07-10, July 2010, available at http://www.fas.usda.gov/wap/circular/2010/10-07/productionfull07-10.pdf.

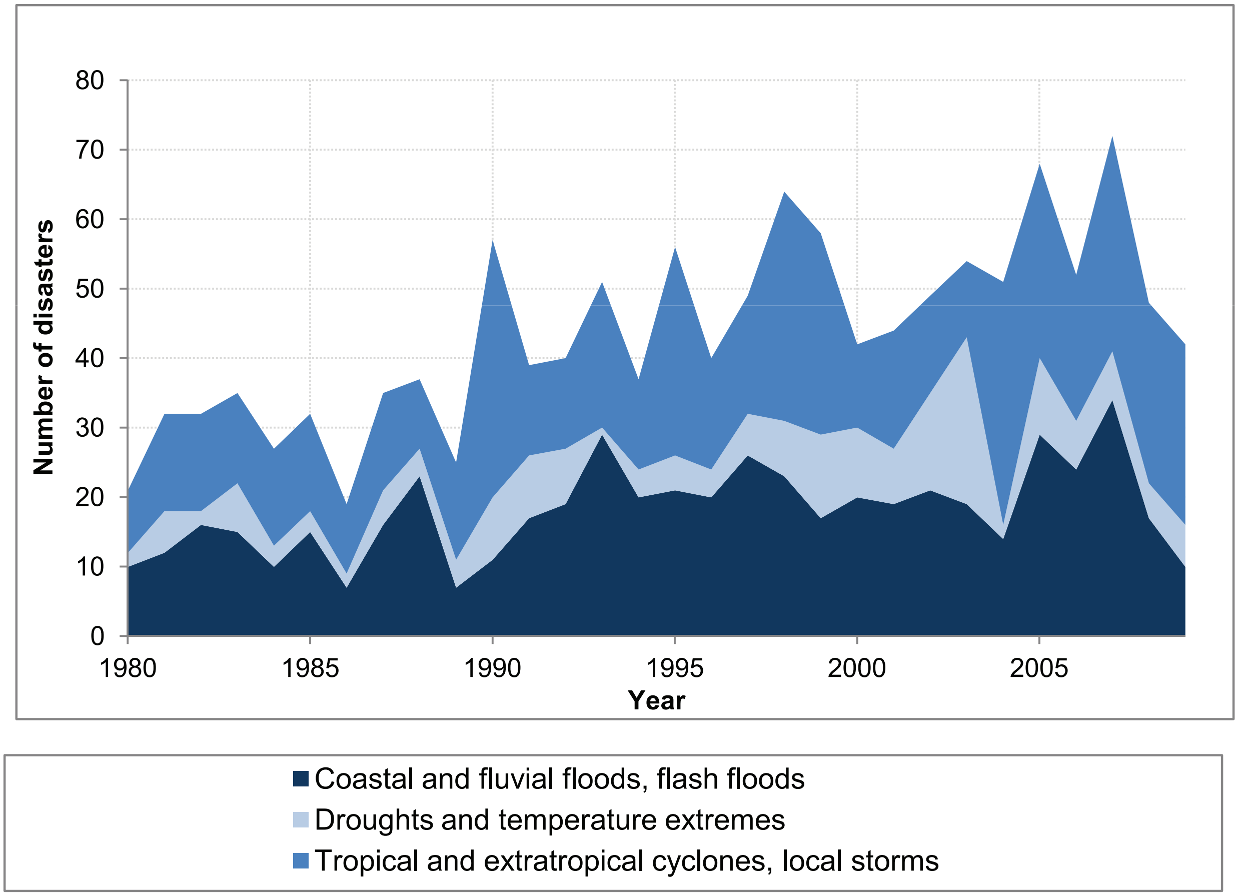

FIGURE 1.1 Global weather-related disasters, 1980-2009. SOURCE: OECD (2012), Global weather-related disasters, 1980-2009, in *OECD Environmental Outlook,* OECD Publishing; available at http://dx.doi.org/10.1787/env_outlook-2012-graph71-en.

Decadal Survey Recommendations

The 2007 decadal survey report was developed over nearly 2 years and through numerous face-to-face meetings by an 18-member steering committee and seven interdisciplinary study panels of approximately 14 members each. Members of these groups were among the nation's leading Earth science researchers and policy experts; in addition, the survey included end users of Earth information data. A key strength of the decadal survey process is that it is informed by the collective wisdom of the broad community. Survey organizers conducted an extensive outreach effort to the larger community, which resulted in numerous town hall and public meetings as well as the submission of more than 100 detailed white papers and conceptual proposals. These submissions came in response to a decadal survey request for information that went out over many outlets to an audience numbering in the many thousands.

BOX 1.1 WEATHER-RELATED NATURAL HAZARDS—A NATION AT RISK

The spring and summer of 2011 brought the United States a string of disastrous weather-related events unmatched in recent years, with 10 events delivering more than $1 billion in impact to the U.S. economy, causing approximately $50 billion in economic losses and resulting in almost 600 fatalities.[1]

- *Wildfires*—Drought-induced wildfires in Texas and Arizona burned more than 3 million acres.
- *Tornadoes*—The April 27, 2011, super-tornado outbreak in Alabama and other southeastern states killed at least 350 people and caused more than $3 billion in insured property losses, making it the deadliest tornado outbreak in 80 years and the costliest in history. Less than a month later a tornado in Joplin, Missouri, on May 22, 2011, killed more than 100 people, the deadliest single twister since 1947. By September 2011, the United States had experienced some 1,784 tornadoes causing 546 fatalities.
- *Flooding*—Extremely heavy rains across the Midwest led to the greatest floods of the Mississippi Valley since 1927. Heavy rains also combined with snowmelt to produce record flooding in the northern Great Plains, with thousands of homes inundated in Minot, North Dakota, and elsewhere. Rains and flooding continued into the summer in many areas, including a 13-inch-plus rainstorm near Dubuque, Iowa, on July 27-28, 2011, that caused the Mississippi to rise 4 feet in a matter of hours.
- *Heat waves*—In July 2011, one of the worst and most prolonged heat waves of recent decades developed over the eastern two-thirds of the country, accompanied by extremely high amounts of moisture. The heat wave set more than 2,000 daily record-high temperatures, taxed power grids to the limit, and resulted in the deaths of dozens of people.
- *Tsunami*—Worldwide, the most damaging natural disaster of 2011 was the Tōhoku earthquake and tsunami that struck Japan on Friday, March 11. Some 16,000 people lost their lives (most as a result of the tsunami that followed the magnitude 9.0 quake), and preliminary estimates by the United Nations Environment Programme placed the damage total at some $309 billion.[2] In the United States, western portions of Washington and Oregon are considered in particular danger of a similar quake and tsunami event.

The human and economic costs of these disasters would have been even greater without satellite observations provided by NASA, NOAA, and international partners that contributed vital input data to weather forecast models (Figure 1.1.1).

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[1]Statistics in the following list are from L. Furgione, U.S. National Weather Service, "Meeting the Nation's Evolving Needs for Space Weather Services: Building a Weather-Ready Nation," presentation to the Maryland Space Business Roundtable, September 29, 2011, available at http://www.nws.noaa.gov/com/files/2011.09.27_spacebusinessroundtable.pdf.

[2]For United Nations estimates of damage, see http://www.unep.org/tsunami/. Casualty estimates from Japan's National Police Agency on September 11, reported in "The Great East Japan Earthquake Disaster: Latest Figures," available at http://nippon.com/en/features/h00004/.

BOX 1.1 CONTINUED

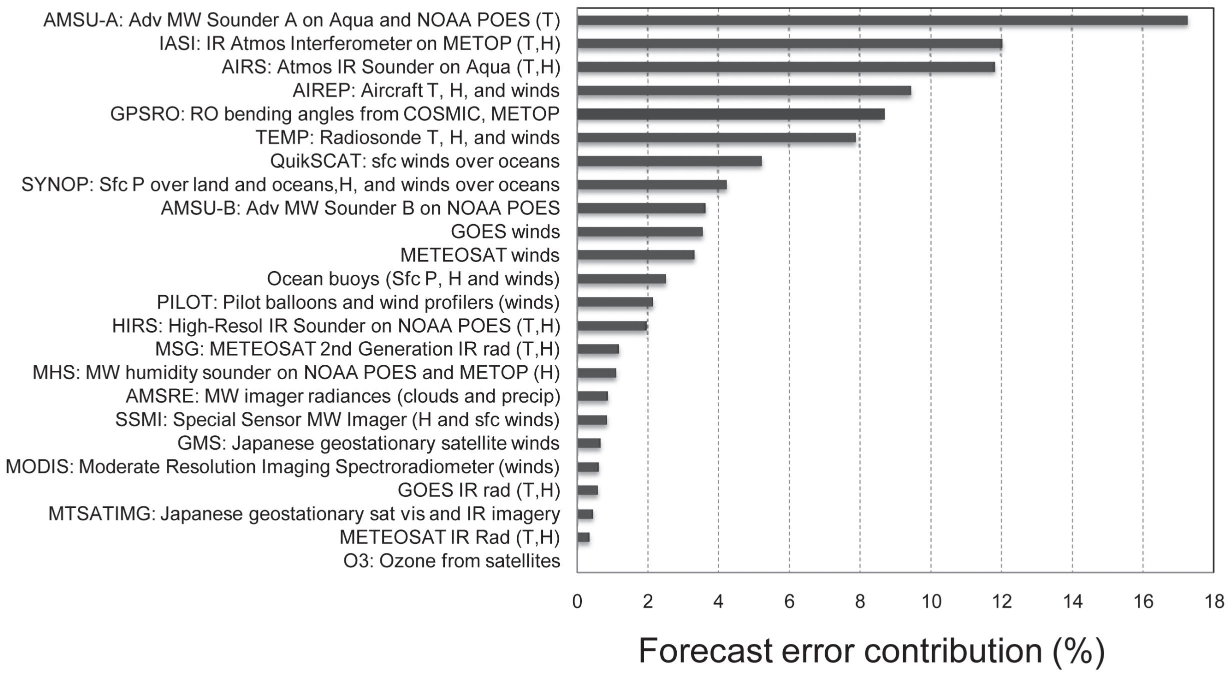

FIGURE 1.1.1 Relative contributions of different Earth observing systems to accuracy in the European Centre for Medium Range Weather Forecasts (ECMWF) weather forecast model, a numerical model that runs out to 10 days that is used by NOAA in developing operational forecasts. The percentage contribution to the reduction of forecast error, which is a measure of errors in temperature, pressure, water vapor, and wind over the entire atmosphere, is shown for each observational system for the period September to December 2008. This measure is a robust indicator of the contribution to the overall accuracy of forecasts of high-impact weather phenomena such as hurricanes, tornadic and winter storms, floods and droughts, and heat and cold waves. The top five observing systems are (1) microwave sounders from satellites, (2) an infrared sounder on the Infrared Atmospheric Sounding Interferometer, (3) the Atmospheric Infrared Sounder (AIRS), (4) aircraft measurements of temperature, winds, and humidity, and (5) Global Positioning Satellite radio occultation sounders on the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) and other satellites. Thus four out of five of the top contributors to forecast accuracy are satellite systems, and all are currently operating beyond their design lifetimes. NOTE: IASI, the Infrared Atmospheric Sounding Interferometer, first launched in 2006 on the nominal 5-year-lifetime METOP-A, is also included on METOP-B, scheduled for launch in May 2012. SOURCE: Courtesy of European Centre for Medium Range Weather Forecasts.

The end result of these efforts was a proposed set of activities that included space missions to be undertaken by NASA and NOAA, as well as supporting and complementary in situ and suborbital programs, programs for sensor and technology development, a robust research and analysis program, and a data analysis, archive, and dissemination program to exploit the enormous quantities of raw data that would result from these activities. The breadth and balance of the 2007 survey's recommendations were both intentional and essential, because increased knowledge of the entire, interconnected Earth system, not just a comprehensive understanding of just one or two of its components, is a primary goal.

Finding: NASA responded favorably and aggressively to the 2007 decadal survey, embracing its overall recommendations for Earth observations, missions, technology investments, and priorities for the underlying science. As a consequence, the science and applications communities have made significant progress over the past 5 years.

However, the implementation of the decadal survey's recommendations has proven difficult. The launch failures of two missions (Orbiting Carbon Observatory and Glory); budgetary shortfalls, the result of both diminished resources and cost growth; and new administration and congressional priorities have resulted in delays, descopes, and cancellations (in some cases at the direction of the Office of Management and Budget). As NASA responds to these and other challenges that may be encountered in implementing the survey, the committee urges NASA to continually refer back to the fundamental goal of nurturing Earth system science, to engage the broad Earth system science community, and to consider the implications of its decisions for the entire portfolio of interconnected activities and—as important—for the next generation of scientists and technologists.

2

Assessing Progress Toward the Decadal Vision

Pre-decadal survey missions—those already in orbit and those in the pipeline—served as the foundation on which the 2007 decadal survey's priorities were established. However, the period from mid-2004 though late 2006, the approximate period when survey members were gathering information and formulating recommendations, was notable for budgetary changes that resulted in the rapid deterioration of this foundation.[1] In the time since the report's release in January 2007, this foundation has continued to erode with the loss of the Orbiting Carbon Observatory (OCO) and Glory missions and the necessity to accommodate further budget shortfalls and cost growth in pre-decadal survey missions still in development. In spite of these setbacks, NASA has made substantial progress on several of the missions that were in development at the time of the survey's release, including the successful launches of the Ocean Surface Topography mission in 2008, as well as Aquarius and the NPOESS Preparatory Project (NPP) in 2011. This chapter summarizes progress toward the 2007 decadal survey's vision through NASA's extended missions, pre-decadal survey missions, implementation of the recommended decadal survey missions, and other key program elements including Climate Continuity missions, Earth Venture missions, the Applied Sciences Program, the suborbital program, technology development, and the research and analysis program.

[1] "Finally, participants in the survey were challenged by the rapidly changing budgetary environment of NASA and NOAA environmental satellite programs. By definition, decadal surveys are forward-looking documents that build on a stable foundation of existing and approved programs. In the present survey, the foundation eroded rapidly over the course of the study in ways that could not have been anticipated. The recommended portfolio of activities in this survey tries to be responsive to those changes, but it was not possible to account fully for the consequences of major shocks that came very late in the study, especially the delay and descoping of the NPOESS program, whose consequences were not known even as this report went to press. Similarly, the committee could not fully digest the ramifications of changes in the GOES-R program of NOAA, and it was in no position to consider the implications of a possible large-scale reduction in funding and later delay of the GPM mission. GPM, a flagship mission of NASA's Earth science program, was a central element in the baseline of programs that the decadal survey committee assumed to be in place when developing its recommendations" (National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007, p. xiv).

EXTENDED MISSIONS

NASA satellites often continue to provide important Earth observations long after the end of their originally planned and funded mission lifetimes (Box 2.1). The biennial NASA Earth Science Senior Review is tasked with evaluating the scientific value of missions that are currently or will soon be operating beyond their planned lifetime. The Senior Review also evaluates mission performance with respect to the health of the instruments and spacecraft, cost, and relevance to national interests.[2] The first Senior Review in 2005 reviewed 12 extended missions and recommended continuation of 10 and termination of 2.[3] The most recent review, in 2011, evaluated 12 extended missions, with all receiving "very high marks for Scientific Merit, Scientific Relevance, and Scientific Product Maturity."[4] All 12 missions were recommended for continuation, but with reduced funding for 2 missions owing to the degradation of some measurements.

Finding: The NASA Senior Review process is working well and provides a fair and open decision pathway for considering extended-life missions in a cost-effective way.

MISSIONS IN THE PRE-DECADAL SURVEY QUEUE

The 2007 decadal survey made its recommendations for new measurements and missions based on the assumed success of NOAA and NASA missions—sometimes referred to as "foundational" missions—that were already in development with launches expected in the early part of the decade following the survey release. These included the Ocean Surface Topography Mission (OSTM), OCO, Glory, Aquarius, NPP, Landsat Data Continuity Mission (LDCM), and Global Precipitation Measurement (GPM) missions.[5] In the years following the release of the survey, NASA continued to focus much of its implementation efforts on completing these foundational missions (Table 2.1).

The successful launch of OSTM in 2008 was followed by two successive disappointments, the launch failures of OCO and Glory, in February 2009 and March 2011, respectively.[6] These launch failures resulted in the loss of key observations of carbon dioxide (OCO), aerosols (Glory), and total solar irradiance (Glory). Subsequently, NASA authorized a replacement mission for OCO, OCO-2, which originally was scheduled for a 2013 launch but now has an uncertain launch date following the loss of Glory, which used the same Taurus XL launch vehicle as OCO. In June 2011, Aquarius/Satélite de Aplicaciones Científicas (SAC)-D, a mission partnership between NASA and the Space Agency of Argentina (Comisión Nacional de Actividades Espaciales) to measure sea-surface salinity, was successfully launched. Aquarius is the first dedicated satellite mission for observing the global salinity field needed for climate studies. Preliminary

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[2]The Senior Review process defines *national interests* as covering applied and operational (non-research) uses, including "operational uses, public services, business and economic uses, military operations, government management, policy making, nongovernmental organizations' uses, etc." See Appendix 2, "National Interest Panel Report," in G. Hurtt (chair), A. Barros, R. Bevilacqua, M. Bourassa, J. Comstock, P. Cornillon, A. Dessler, G. Egbert, H.-P. Marshall, R. Miller, L. Ritchie, et al., *NASA Earth Science Senior Review 2011*, submitted to Dr. Michael Freilich, Director, Earth Science Division Science Mission Directorate, June 30, 2011, available at http://science.nasa.gov/media/medialibrary/2011/07/22/2011-NASA-ESSR-v3-CY-CleanCopy_3x.pdf. The particular implementation of the Senior Review that is employed by NASA's Earth Science Division is consistent with that recommended in the National Research Council report *Extending the Effective Lifetimes of Earth Observing Research Missions* (The National Academies Press, Washington, D.C., 2005).

[3]See http://modis.gsfc.nasa.gov/sci_team/meetings/200610/presentations/plenary/volz.ppt.

[4]See NASA, *NASA Earth Science Senior Review 2011,* 2011, p. 5.

[5]The GPM mission consisted of two spacecraft—a core spacecraft and a low-inclination orbiter.

[6]The two failures were attributed to the Taurus XL launch vehicle, thus creating significant uncertainty in the planning for launch vehicles for future missions for many years into the future (see in Chapter 3 the section "Access to Space").

BOX 2.1 ONGOING CONTRIBUTIONS FROM NASA'S EARTH SCIENCE EXTENDED MISSIONS

NASA's aging Earth science satellite fleet continues to support many advances in Earth science and applications. Some recent examples include the following:[1]

- Contributing to the accuracy of weather forecasts and warnings;
- Extending and improving the record of sea-level measurement through continuation of the Jason mission using the precise geodetic infrastructure maintained largely by NASA (Figure 2.1.1);
- Obtaining unique perspectives on water mass changes, including ice loss and the water stored in major river basins around the world, through continuation of the GRACE missions (Figure 2.1.2);
- Continuing the record of stratospheric ozone depletion and recovery through continuation of the Aura mission;
- Understanding the link between fires and air quality through continuation of the Terra, Aqua, and Aura missions;
- Maintaining a continuous, precise measure of the solar energy reaching Earth through continuation of the Solar Radiation and Climate Experiment (SORCE);
- Providing ongoing observations for improved hurricane prediction through continuation of the Tropical Rainfall Measuring Mission (TRMM);
- Determining the relationship between Earth's radiation budget and cloud systems and precipitation, and characterizing clouds' microphysics, morphology, and convection through the continuation of CloudSat;
- Collecting the only civilian high-spectral-resolution imagery available through the continuation of EO-1 and 36 bands of global multispectral environmental imagery through the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua;
- Producing a high-quality time series of global sea-surface topography through the continuation of the Ocean Surface Topography Mission (OSTM);
- Measuring cloud optical depth and cloud depth and detecting cloud occurrence through the continuation of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite; and
- Estimating wind speed and direction over the ocean through the continuation of the Quick Scatterometer (QuikSCAT).

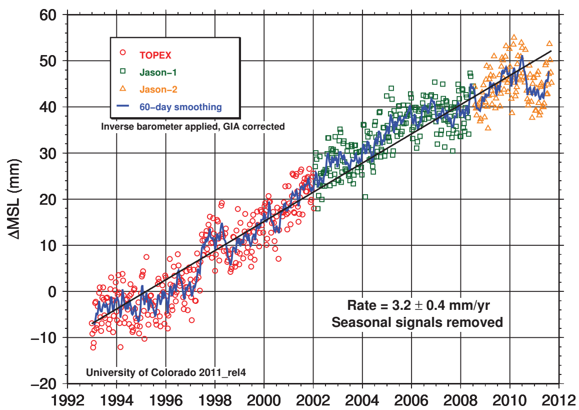
[1] See http://science.nasa.gov/media/medialibrary/2011/07/22/2011-NASA-ESSR-v3-CY-CleanCopy_3x.pdf.

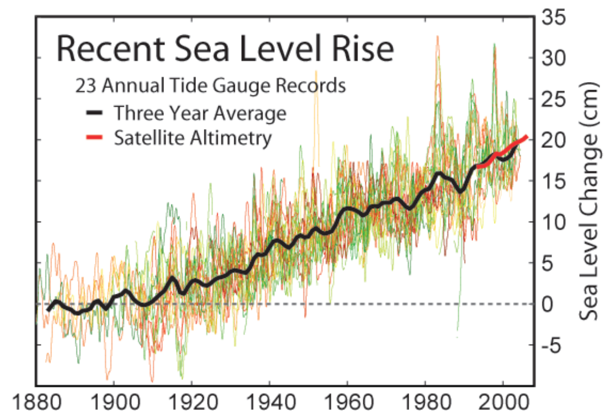
data have shown encouraging results (Figure 2.1). In October 2011, the NPOESS Preparatory Project was successfully launched, and in December 2011 the first images from its VIIRS instrument were acquired.

LDCM is intended to replace the aging Landsat 7 mission to provide continuity of land cover measurement. Although the 2007 decadal survey recommended securing such a replacement before 2012,[7] LDCM is currently slated for launch no earlier than December 2012. This delay was in part due to the congressionally directed addition of the thermal infrared sensor (TIRS) to the platform. GPM, recommended in the survey to "launch in or before 2012" to ensure continuity of precipitation measurements, is now targeted

[7] National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 6.

BOX 2.1 CONTINUED





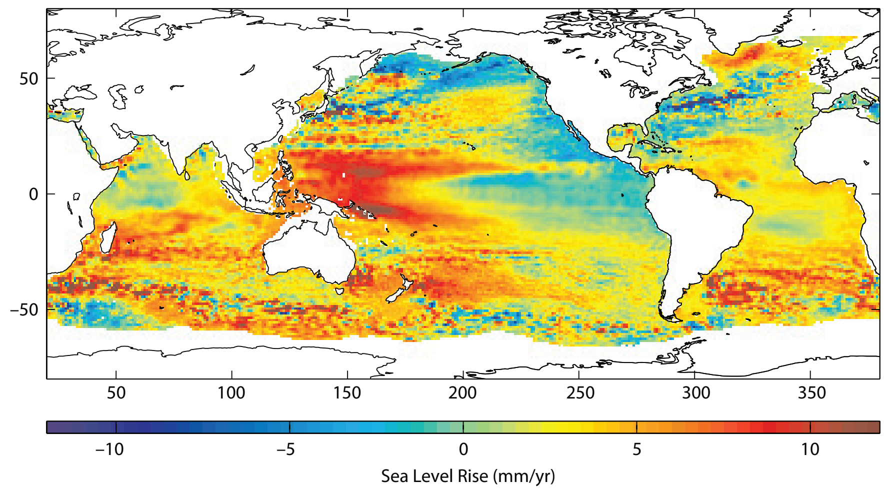


FIGURE 2.1.1 *Top left:* Global mean sea level from satellite altimetry observations: TOPEX/Poseidon (blue), Jason-1 (red), Jason-2 (black). Dots represent 10-day averages; curves represent 60-day smoothing. A trend of 3.2 ± 0.4 mm/year is estimated. Although slightly different results have been derived by other investigators using data products based on different processing methods, they generally fall within the quoted uncertainty of the estimate. *Top right:* Change in annually averaged sea level at 23 geologically stable tide gauge sites with long-term records as selected by B.C. Douglas, Global sea rise: A redetermination, *Surveys in Geophysics* 18:279-292, 1997. The thick dark line is a 3-year moving average of the instrumental records. For comparison, the annually averaged satellite altimetry data from TOPEX/Poseidon are shown in red. Note that the data scatter in the tide gauge measurements is ± 5 cm, whereas it is ± 0.5 cm in the altimeter measurements. *Bottom:* Trend in millimeters per year of regional sea level change from 1993 to 2009 based on satellite altimetry observations. SOURCE: *Top left:* R.S. Nerem, Global Mean Sea Level Time Series, Release 2012-1, Sea Level Research Group, University of Colorado, February 13, 2012; http://sealevel.colorado.edu/. *Top right:* Robert A. Rohde, Global Warming Art. *Bottom:* J.K. Willis, D.P. Chambers, C.-Y. Kuo, and C.K. Shum, Global sea level rise: Recent progress and challenges for the decade to come, *Oceanography* 23(4):26-35, 2010.

BOX 2.1 CONTINUED

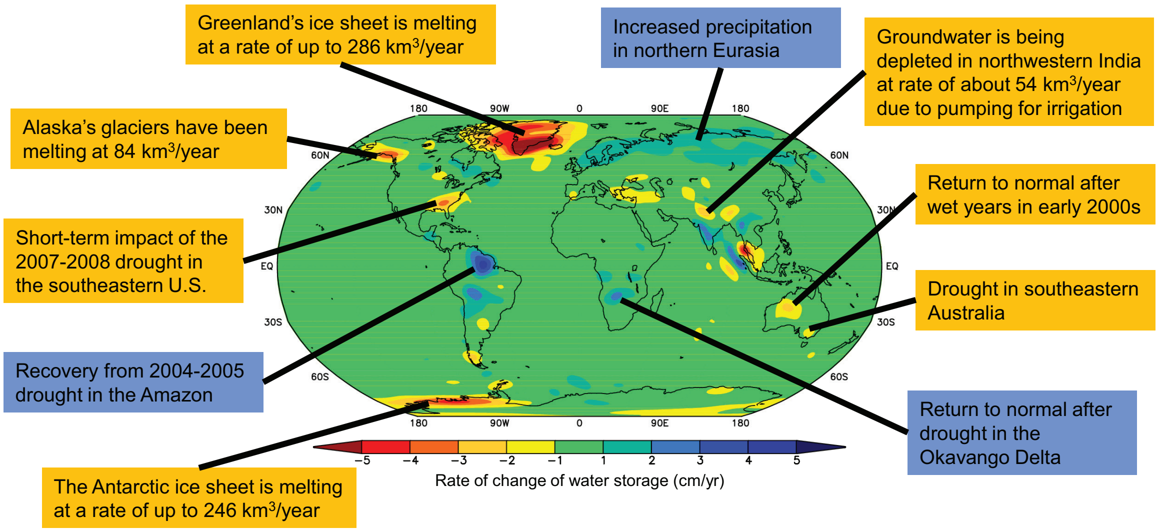


FIGURE 2.1.2 Trends in terrestrial water storage, including groundwater, soil, water, lakes, snow, and ice as observed by GRACE during 2002-2009. The GRACE mission observes changes in water storage caused by natural variability, climate change, and human activities such as groundwater pumping. Using data products based on different processing methods, other investigators have derived various estimates of these trends, but the signs of the largest trends remain quite robust. SOURCE: Courtesy of Matthew Rodell, NASA Goddard Space Flight Center; M. Rodell, J.S. Famiglietti, and D.P. Chambers, Climate-related trends, human-induced trends, and false trends in seven years of terrestrial water storage observations from GRACE, *Eos Transactions, American Geophysical Union* 90:(52), Fall Meeting Supplement, Abstract H11C-0810, 2009.

to launch in July 2013. In the fiscal year (FY) 2012 budget, the GPM mission was descoped to include only the core spacecraft, with development of the low-inclination orbiter canceled.

> **Finding:** Progress in the pre-decadal survey missions has fallen short of expectations because of launch failures, delays, and changes in scope. NASA's primary programmatic emphasis remains on flying out its pre-decadal survey mission queue.

DECADAL SURVEY MISSIONS

The 2007 decadal survey was well received by NASA[8] and Congress, and NASA initiated plans to implement the mission recommendations by beginning formulation studies for the first phase of survey

[8]For example, in testimony on March 7, 2007, before the Senate Committee on Commerce, Science and Transportation Subcommittee on Space, Aeronautics and Related Sciences, NASA's director for the Earth Science Division, Michael Freilich, stated, "We welcome the Decadal Survey—indeed, we asked for it.… The science priorities identified by the Decadal Survey will be our primary guide as we design and select Earth observing missions to be flown in the next 10-15 years. Considering the long time horizon in the NRC's report, it will require several budget cycles to implement the program that we will derive from the Decadal Survey's near- and mid-term recommended mission sets. Nevertheless, our planning process starts with the consensus scientific priorities articulated

TABLE 2.1 Current Status of Pre-Decadal Survey Missions

Mission	Launch Date	Status
OSTM/Jason-2 (Ocean Surface Topography Mission)	June 2008	Operating
OCO (Orbiting Carbon Observatory)	February 2009	Launch failure
Glory	March 2011	Launch failure
Aquarius	June 2011	Operating
NPP (NPOESS Preparatory Project)	October 2011	Operating
LDCM (Landsat Data Continuity Mission)	Targeting December 2012	Implementation
GPM Core (Global Precipitation Mission)	Targeting July 2013	Implementation
GPM LIO (Global Precipitation Mission—low inclination orbiter)	—	Canceled

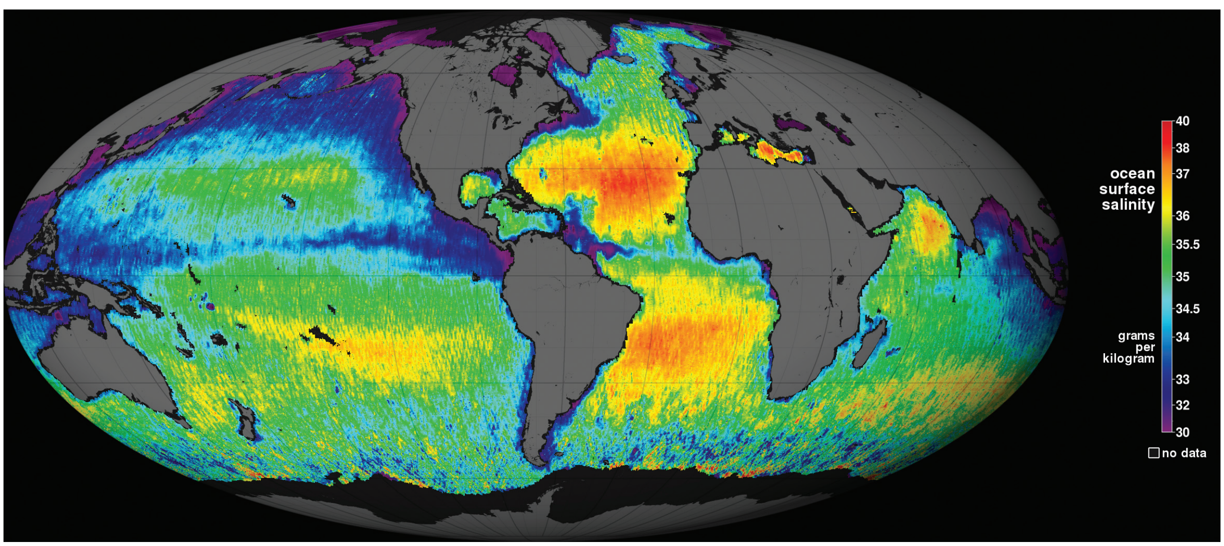


FIGURE 2.1 The first global map of the salinity of the ocean surface from the Aquarius mission, providing an early glimpse of the mission's anticipated results. The map is a composite of the data from August 25, 2011 (the day Aquarius became operational), to September 11, 2011, and illustrates the most advanced measurement of ocean salinity from space. After further calibration and validation, this spacecraft will be able to remove some sources of error and make Aquarius measurements more accurate than those made from other platforms. SOURCE: Courtesy of NASA/GSFC/JPL-Caltech; PIA14786.

missions.[9] Two of those missions, SMAP (Soil Moisture Active-Passive) and ICESat-2, have since entered into their implementation phases while the other two, DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) and CLARREO (Climate Absolute Radiance and Refractivity Observatory), remain in formulation. The FY2012 budget significantly delays both DESDynI and CLARREO compared to the FY2011 plan, which would have had both missions enter development in 2011.[10]

A mission-by-mission summary of progress on each decadal survey mission recommendation is given in Table 2.2. From these data, it is clear that the survey's recommended new measurement missions are proceeding at a considerably slower pace than recommended. The 2007 decadal survey envisioned launching three phases of missions by 2020, whereas the current NASA budget does not complete even the first phase of missions by this date. Some reasons for and consequences of this delay are explored in Chapter 3. The result is that the Earth science program and its science community face a major decline in the number of missions and the instruments in orbit, because new mission launches will not keep pace with the anticipated loss of missions already in extended operations.

Finding: Implementation of the new measurement missions recommended in the 2007 decadal survey has proceeded much more slowly than the pace originally envisioned.

Given the objective of advancing Earth system science—an objective embraced by NASA's Earth Science Division—there is a particular need to make decisions regarding the scope, cost, and schedule of an individual mission in the context of the larger decadal survey-recommended portfolio.[11] Further, absent a countervailing mechanism, there is a natural tendency for individual missions to become more responsive to single communities or disciplines rather than to the overall Earth system science community.[12] For example, changes to the survey-recommended ICESat-2 mission were, in part, the result of pressures from a disciplinary community whose desires for a more advanced and capable mission than envisioned by the survey were not restrained by consideration of the budgetary impact on development of future missions

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for us by the NRC." Dr. Freilich's full statement is available at http://www.hq.nasa.gov/legislative/hearings/. On October 25, 2009, NASA provided a written response to the recommendations of the decadal survey (an unpublished letter from Edward Weiler, Associate Administrator, NASA's Science Mission Directorate, to Charles Kennel, Director, NRC Space Studies Board). Congressional reaction immediately following the release of the survey on January 7, 2007, included the following statement from House Science and Technology Committee Chair Bart Gordon: "At a time when accurate weather forecasting and climate research is becoming increasingly important to the well-being of our citizens, this distinguished panel of experts is warning in no uncertain terms that 'the United States' extraordinary foundation of global observations is at great risk'" (statement issued on January 16, 2007).

[9]Appendix E of this report details NASA's response in 2009 to the recommendations made in the Earth science and applications from space decadal survey (National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007), as well as the agency's status update given to the Committee on the Assessment of NASA's Earth Science Program on April 27, 2011, at its first meeting in Washington, D.C.

[10]In the 2010 NASA report *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space* (available at http://nasascience.nasa.gov/earth-science/), CLARREO (the first of two mission components) and DESDynI (two spacecraft sharing a single launch vehicle) were slated for launch in 2017. The committee was informed at its first meeting on April 28, 2011, by the director of NASA's Earth Science Division, Michael Freilich, that these plans are now on hold because the fiscal year 2012 budget does not fund mission implementation; no new target launch dates are available for these missions.

[11]NASA has a program executive and program scientist for each mission, and individual projects have project managers, project scientists (or principal investigators), science teams, and engineering teams; however, there is no formal coordinating mechanism across the portfolio of missions to handle decisions of cost, scope, and schedule. Instead, these are handled through individual projects, typically through reviews.

[12]"Where possible within budget constraints, augmentation of the specified set of science observations with additional desired observables should be considered; however, NASA and the scientific community must avoid 'requirements creep' and the consequent damaging cost growth" (National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 43).

serving different communities.[13] Especially in light of austere budget projections, a large increase in the cost of a particular survey mission may threaten execution of the balanced portfolio recommended by the decadal survey.

Climate Continuity Missions[14]

NASA has responsibilities to all of its stakeholders, including the executive branch and Congress, which have interests in Earth observations that extend beyond those of the science and applications community whose consensus priorities are reflected in the decadal survey. From an applications standpoint, these include observations in support of policy development and long-term monitoring to document important trends in a rapidly changing Earth. In an effort to balance executive branch and congressional priorities with the community guidance set forth in the survey, NASA issued a report, *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space*,[15] which convolved survey and administration priorities and took advantage of new funds made available by the executive branch to accelerate its priorities. The committee was informed that this document, which was approved by the Office of Science and Technology Policy (OSTP), the U.S. Global Change Research Program (USGCRP), and the Office of Management and Budget (OMB), now serves as the governing plan for NASA's Earth science program.

The committee is encouraged by the inclusion in the NASA report of a new line of Climate Continuity missions that is responsive to the survey's call for sustained observations to complement the new measurements it recommends. Through this line of missions, NASA has accepted responsibility for some sustained observations, which are especially needed in view of the demonstrated inability of NOAA to take up this mission in an operational capacity. However, the committee remains concerned that a long-term strategy for selecting and funding such measurements has yet to be established (see Chapter 4 for further discussion). Without a firm agency or multiagency plan and corresponding funding made available to accommodate sustained measurements, funding for these continuity missions must come at the expense of survey priorities for new measurements. Lack of sufficient funding in near-term budgets to cover both continuity missions and new measurement missions heightens the need to determine these priorities sooner rather than later. A process is urgently needed for deciding which measurements are to be sustained and how balance can be achieved between sustained and new measurements in the face of flat or declining budgets. (See discussion and committee recommendations in Chapter 4.)

Earth Venture Missions

The 2007 decadal survey recommended establishment of a new Earth Venture class of relatively low-cost research and applications missions to restore more frequent launch opportunities and facilitate demonstration of innovative ideas and higher-risk technologies. These missions were envisioned as including "stand-alone missions that use relatively simple, small instruments, spacecraft, and launch vehicles; more complex instruments of opportunity flown on partner spacecraft and launch vehicles; or complex sets of instruments flown on suitable suborbital platforms to address focused sets of scientific questions."[16]

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[13] The evolution toward more discipline-specific priorities for ICESat-2 was discussed in detail during a Committee on the Assessment of NASA's Earth Science Program teleconference with NASA Chief Scientist Waleed Abdalati on August 8, 2011.

[14] The Climate Continuity missions include SAGE-III (2015), OCO-3 (2015), GRACE-FO (2016), and PACE (2019-2020).

[15] NASA, *Responding to the Challenge of Climate and Environmental Change,* 2010.

[16] National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 59.

TABLE 2.2 Current Status of Earth Science and Applications Decadal Survey Recommended Missions

Mission	Mission Description (from 2007 decadal survey)	Recommended Launch Time Frame	Planned Launch Date	Status[a]
CLARREO (Climate Absolute Radiance and Refractivity Observatory)	Solar and Earth radiation; spectrally resolved forcing and response of the climate system	2010-2013	None[b]	Formulation (Pre-Phase A)
SMAP (Soil Moisture Active-Passive)	Soil moisture and freeze-thaw for weather and water-cycle processes	2010-2013	November 2014	Implementation Phase (Phase B)
ICESat-II	Ice sheet height changes for climate change diagnosis	2010-2013	October 2015	Implementation Phase (Phase A)
DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice)	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	2010-2013	None[b]	Formulation (Pre-Phase A)
HyspIRI (Hyperspectral Infrared Imager)	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	2013-2016	None	Formulation (Pre-Phase A)
ASCENDS (Active Sensing of CO_2 Emissions over Nights, Days, and Seasons)	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	2013-2016	None[c]	Formulation (Pre-Phase A)
SWOT (Surface Water and Ocean Topography)	Ocean, lake, and river water levels for ocean and inland water dynamics	2013-2016	None[d]	Formulation (Pre-Phase A)
GEO-CAPE (Geostationary Coastal and Air Pollution Events Mission)	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	2013-2016	None	Formulation (Pre-Phase A)
ACE (Aerosol/Cloud/Ecosystems Mission)	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	2013-2016	None	Formulation (Pre-Phase A)
LIST (Lidar Surface Topography)	Land surface topography for landslide hazards and water runoff	2016-2020	None	Formulation (Pre-Phase A)
PATH (Precipitation and All-weather Temperature and Humidity)	High-frequency, all-weather temperature and humidity soundings for weather forecasting and sea-surface temperature[e]	2016-2020	None	Formulation (Pre-Phase A)
GRACE-II (Gravity Recovery and Climate Experiment-II)	High-temporal-resolution gravity fields for tracking large-scale water movement	2016-2020	None[f]	Formulation (Pre-Phase A)
SCLP (Snow and Cold Land Processes)	Snow accumulation for freshwater availability	2016-2020	None	Formulation (Pre-Phase A)
GACM (Global Atmospheric Composition Mission)	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	2016-2020	None	Formulation (Pre-Phase A)

TABLE 2.2 continued

Mission	Mission Description (from 2007 decadal survey)	Recommended Launch Time Frame	Planned Launch Date	Status[a]
3D-WINDS (Demo) (3D Tropospheric Winds from Space-based Lidar)	Tropospheric winds for weather forecasting and pollution transport	2016-2020	None	Formulation (Pre-Phase A)

[a]During Pre-Phase A, a pre-project team studies a broad range of mission concepts that contribute to program and mission directorate goals and objectives. These advanced studies, along with interactions with customers and other potential stakeholders, help the team to identify promising mission concepts and draft project-level requirements. The team also identifies potential technology needs (based on the best mission concepts) and assesses the gaps between such needs and current and planned technology readiness levels. See NASA NPR 7120.5, available at http://www.hq.nasa.gov/office/codeq/doctree/71205.htm.

During Phase A, a project team is formed to fully develop a baseline mission concept and begin or assume responsibility for the development of needed technologies. This work, along with interactions with customers and other potential stakeholders, helps with the baselining of a mission concept and the program requirements on the project. These activities are focused toward System Requirements Review (SRR) and System Definition Review (SDR/PNAR) (or Mission Definition Review (MDR/PNAR)). See NASA NPR 7120.5, available at http://www.hq.nasa.gov/office/codeq/doctree/71205.htm.

During Phase B, the project team completes its preliminary design and technology development. These activities are focused toward completing the Project Plan and Preliminary Design Review (PDR)/Non-Advocate Review (NAR). See NASA NPR 7120.5, available at http://www.hq.nasa.gov/office/codeq/doctree/71205.htm.

[b]In the 2010 NASA report *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space* (available at http://nasascience.nasa.gov/earth-science/), CLARREO (the first of two mission components) and DESDynI (two spacecraft sharing a single launch vehicle) were slated for launch in 2017. The committee was informed at its first meeting on April 28, 2011, by the director of NASA's Earth Science Division, Michael Freilich, that these plans are now on hold because the fiscal year 2012 budget request does not fund mission implementation; no new target launch dates are available for these missions.

[c]Mission planned for launch by end of 2019 per NASA, *Responding to the Challenge of Climate and Environmental Change* (2010); however, a formal target launch date is not determined until after Mission Concept Review, when a budget wedge is established.

[d]Mission planned for launch by the end of 2020 per NASA, *Responding to the Challenge of Climate and Environmental Change* (2010); however, a formal target launch date is not determined until after Mission Concept Review, when a budget wedge is established.

[e]Cloud-independent, high-temporal-resolution, lower-accuracy sea-surface temperature measurements to complement, not replace, global operational high-accuracy sea-surface temperature measurements.

[f]The GRACE Follow-on Mission, a climate continuity mission called for in NASA's June 2010 climate-centric architecture report, will provide many of the observations envisioned by the 2007 decadal survey for GRACE-II.

NASA has since implemented the Earth Venture mission line in keeping with the survey recommendation. The first Earth Venture solicitation (EV-1) was targeted toward suborbital investigations and resulted in the selection of five proposals in May 2010. These suborbital (piloted and unpiloted aircraft) missions are currently in their implementation phase. In June 2011, NASA released the first Earth Venture stand-alone mission solicitation (EV-2), with selections planned for 2012. Going forward, NASA plans to release Earth Venture stand-alone solicitations every 4 years, suborbital solicitations every 4 years, and instrument of opportunity solicitations every 15-18 months beginning in 2011.[17] This solicitation schedule is supported by a dedicated and protected funding line.

The Earth Venture-class program has the added value of enabling individual university principal investigator (PI)-type missions to pursue specific science questions, as opposed to the broader science

[17]M. Freilich, Director, Earth Science Division, NASA, presentation to the Committee on the Assessment of NASA's Earth Science Program, April 27, 2011.

investigations that usually accompany the larger facility-class missions. The overall Earth Venture program includes airborne, instrument, and mission opportunities that are small enough to permit the involvement of graduate students and younger scientists with relatively low risk, such that it can serve to revitalize the remote sensing component of the Earth science community, as well as potentially create a cadre of young, experienced PIs. The Earth Venture-class space program has generated widespread community interest, with 30 proposals submitted in response to the first solicitation. However, the current frequency of Earth Venture space mission solicitations of only one every 4 years is too low to meaningfully address this demand; thus, the committee recommends a modest increase in frequency consistent with available budgets and maintaining a balance between Earth Venture-class missions and the larger decadal survey-recommended missions that are needed to form the background of a robust and broad Earth science program.

Finding: The Earth Venture-class program is being well implemented by NASA and is a crucial component of fulfilling the 2007 decadal survey's objectives.

Recommendation: Consistent with available budgets and a balanced Earth observation program from space based on the 2007 decadal survey recommendations, NASA should consider increasing the frequency of Earth Venture stand-alone/space-based missions.

APPLIED SCIENCES PROGRAM

The knowledge gained from a program of space observations looking down at Earth is of direct relevance to the social and economic vitality, as well as the security, of the nation. The characteristics of Earth observation programs in general and NASA and NOAA programs in particular reflect this unique character.[18] The 2007 decadal survey charge included an analysis of "measurements, … capabilities and supporting activities within NASA ESE (Earth Science Enterprise) and NOAA NESDIS to support national needs … climate and global change, … weather forecasting, seasonal climate prediction, aviation safety, natural resources management, agricultural assessment, homeland security, and infrastructure planning."[19] The survey envisioned that benefits from future missions would "range from information for short-term needs, such as weather forecasts and warnings for protection of life and property, to the longer-term scientific understanding necessary for future applications that will benefit society in ways still to be realized."[20] ESD has mounted an evolving effort to enable ongoing involvement of applications perspectives and engagement of applications-oriented communities in decadal survey mission planning.[21] Although these activities started as ad hoc efforts, more formal arrangements are unfolding as ESD builds capability in this direction.[22]

[18]For example, some Earth observations are time critical—deferring or stopping observations may carry societal and/or economic costs. Communities of users and agencies across the government from the Federal Emergency Management Agency to the Department of Agriculture to NOAA rely on the availability of Earth data products. As the utility and value of new "research" observations are demonstrated, there is typically strong support for making the observations "operational" and for ensuring their future availability.

[19]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 383.

[20]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. xi.

[21]Capacity building within the applications user community requires a sustained, long-term commitment. Developing the skills, decision support tools, and demand for space-based products in a given applications community takes time, and the applications program should maintain a balance between sustained support in critical areas (for example, areas linked to decadal survey-recommended data products) and innovation-focused studies to develop new possibilities.

[22]ESD has held workshops to engage the applications community and to ensure that applications are seen as a dimension of the

Within ESD the Applied Sciences Program has the primary responsibility for leading and organizing efforts and interactions between applications communities and mission teams, including ensuring "that NASA's flight missions plan for and support applications goals in conjunction with their science goals, starting with mission planning and extending through the mission life cycle."[23] The involvement of the Applied Sciences Program in the decadal survey missions has been mostly in the context of sponsoring applications scientists to participate on their science definition teams[24] (notably the Soil Moisture Active-Passive mission; see Box 2.2). However, focused applications teams in air quality (selected in 2010) and SERVIR and a solicitation in process for 2012 incorporate a planning element that is intended to promote use of decadal survey mission data for societal benefits in general.

The Applied Sciences Program also leads crosscutting studies related to applications needs and funds individual efforts through a solicitation process. As an example of the former, the program is leading a study to assess data latency targets, particularly with respect to the needs of applied and operational users, for the suite of planned missions.[25] This effort will examine data product management practices and/or organizational arrangements that may support enhanced production and delivery for priority products. The results of the study will be used to inform decadal survey mission planning and design trade-offs.

The Applied Sciences Program facilitates remote-sensing-observation use by other government agencies and the private sector through peer-reviewed competitions centered on themes selected to align with categories of societal benefits identified by the U.S. Group on Earth Observations (USGEO),[26] including applications of Earth science observations to agriculture, air quality, climate, ecological forecasting, natural disasters, public health, water, energy, and weather.[27,28] Numerous examples of such funded efforts

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decadal survey-recommended missions. For example, in February 2010, ESD held an Earth observing missions applications workshop to introduce applications experts to the mission planning process and lexicon (e.g., mission development phases and major milestone/decision points). The workshop was also intended to identify lessons learned from EOS missions that contributed to practical applications, to share ideas on ways to engage the applications communities, and to identify synergies between missions. Additionally, in July 2010, ESD held special applications-oriented sessions at the IEEE International Geoscience and Remote Sensing Symposium, with workshops titled "Applications Bridging the Period between EOS and the Decadal Survey Eras" and "Realizing the Applications Benefits from NASA's Pathfinding EOS Missions—The 1st Generation."

[23]Strategic Goal 3 in NASA, *NASA Earth Science Division Applied Sciences Program. Program Strategy: 2010-2015,* NASA, Washington, D.C., available at http://cce.nasa.gov/pdfs/ASPProgramStrategy.pdf, p. 4.

[24]Connections between the decadal survey mission teams and end-user applications teams are fundamental to the successful use of measurements in support of national needs. Early in a mission, as requirements and designs are developed and subsequently refined, users provide critical input for systems engineering of the mission. As the systems are developed, continued user involvement is needed to ensure that the value of the data is optimized even as the designs are modified. As the mission approaches launch, there is a need to ensure that the applications community is adequately prepared to receive and use the mission data and products in their respective areas. Thus, applications community involvement is not a one-time event, but rather an ongoing working relationship that requires a sustained commitment by both parties.

[25]According to NASA, "Data latency is a major factor in the utility of data products for applied and operational uses and some scientific investigations. Many missions have data products that may be extremely valuable if they can reach the applied communities quickly after collection." The study NASA has commissioned "will support the Earth Science community to assess options for meeting latency desires on the missions and inform trade-off decisions regarding mission costs and design." (L. Friedl, "NASA Science Mission Directorate: Earth Science Division," presentation to the Earth Science Information Partners Federation Partnership Panel, 2012 Winter Meeting, January 4, 2012. For more information, see http://wiki.esipfed.org/images/c/c8/ESIP_2012_-_Friedl_Partnership _Panel.pdf.)

[26]See http://usgeo.gov/.

[27]Uses of NASA Earth observations by other federal agencies include U.S. Navy use of MODIS aerosol observations, Department of Defense use of MODIS during Operation Iraqi Freedom, state and federal agency use of thermal infrared measurements for water management in the western United States, and agency support in disaster response. The NPOESS Preparatory Project is intended to build on the pioneering observations from NASA's Earth Observing System project to provide NOAA and other operational agencies access to data taken by the next-generation operational imager and sounders—the Visible Infrared Imaging Spectroradiometer Suite, Crosstrack Infrared Sounder, and Advanced Technology Microwave Sounder. Private sector applications include utility power load forecasting and mapping and detection of change for natural resource management.

[28]NASA, *Science Serving Society: NASA Earth Science Division Applied Sciences Program Annual Report,* 2009, available at http://appliedsciences.nasa.gov/pdf/NASA_ASP_AR_090310_Fin_V2-web.pdf.

BOX 2.2 SMAP MISSION APPLICATIONS ENGAGEMENT: A BEST PRACTICE

The Soil Moisture Active-Passive (SMAP) mission established a formal Applications Working Group and a plan that leverages modest NASA funding to entrain end users at the grassroots level.[1] SMAP also created an "early adopters effort" to prepare for SMAP data products.[2] In line with recommendations of the 2007 decadal survey report,[3] SMAP is implementing a strategy that promotes applications research and engages a broad community of users in SMAP applications. The SMAP Applications Working Group has written an applications plan and held two applications-focused workshops.[4] The goals of the SMAP applications program are to (1) promote the use of SMAP products to a community of end users and decision makers that understand SMAP capabilities and are interested in using SMAP products in their application; (2) facilitate feedback between SMAP user communities through the SMAP Applications Working Group and the SMAP mission and science definition team; and (3) provide information on and documentation of collaboration with different classes of users and communities and design communication strategies to reach out to these new communities, including those concerned with precipitation, drought detection, agriculture, and ecosystem modeling, among others.[5]

The preliminary SMAP applications plan[6] provides science requirements and input from the SMAP Applications Working Group. It calls for establishing strategic alliances with key organizations within the Department of Defense, U.S. Department of Agriculture (USDA), National Oceanic and Atmospheric Administration (NOAA), the Department of the Interior, and the U.S. Geological Survey (USGS). The SMAP applications workshops have included participation by the NOAA/National Weather Service; USDA National Agricultural Statistics Service, USDA Risk Management Agency, and USDA Agricultural Research Service; National Integrated Drought Information System; National Center for Atmospheric Research; AgCanada; U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory; Bureau of Reclamation; Air Force Weather Agency; StormCenter Communications; Dartmouth Flood Observatory; Meteorological Service of Canada; USGS; a global insurance broker; and numerous universities and other institutions. The agendas and presentations from these meetings[7] make it clear that the project is reaching out to its identified end users and looking for ways to entrain even more of them.[8] The last workshop, for example, included topics ranging from crop casting and food security to engaging the insurance and financial services sector. Participants identified end uses of the data, such as providing post-fire forest monitoring through integration with the Burned Area Emergency Rehabilitation plans, forecasting crop yields via infusion into the National Agricultural Statistics Service weekly crop condition, and verifying claims and loss accumulation from floods. The SMAP applications plan[9] outlines its strategy to entrain early adopters,[10] communicate to broad communities of potential end users, and target specific organizations that can benefit from its measurements. These groups include the United Nations Food and Agriculture Organization, the European Union Joint Research Council, the USDA Foreign Agriculture Service, and the U.S. Agency for International Development.

Beyond these examples of early engagement with communities that will put Earth science observations to practical use, other instances provided in Appendix C illustrate far-reaching governmental operational use of research satellite data and new data products (e.g., related to airborne dust, fire monitoring, volcanic ash advisories, flood disaster response, and improved forecasts for the U.S. Navy, as well as short-term weather forecasts), along with examples of more general research results with societal relevance (e.g., accelerated melt from dust deposits on snow, forest and timber productivity forecasting, sea-level rise impacts, negative health impacts of air pollution, and groundwater loss). These examples suggest how governmental operational use of decadal survey mission data will grow as utilization extends from early adopters to the broader community.

The DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice), GEO-CAPE (Geostationary Coastal and Air Pollution Events), and HyspIRI (Hyperspectral Infrared Imager) missions are also active in engaging the applications community in pre-Phase A mission planning and mission definition.[11]

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[1]See http://smap.jpl.nasa.gov/science/wgroups/applicWG/.

BOX 2.2 CONTINUED

[2]In this context, early adopters are groups that have a direct or clearly defined need for soil moisture or freeze/thaw data, and that are planning to apply their own resources to demonstrate the utility of SMAP data for their particular system or model. SMAP selected six organizations and is developing a memorandum of agreement with these organizations.

[3]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

[4]The SMAP Applications Working Group coordinates applications activities for the mission. The working group has developed a SMAP applications plan, and is coordinating the engagement of SMAP applications early adopters. The working group held the First SMAP Applications Workshop at the NOAA Science Center, Silver Spring, Md., on September 9-10, 2009. The Second SMAP Applications Workshop was held October 12-13, 2011, at the U.S. Department of Agriculture in Washington, D.C.

[5]See http://smap.jpl.nasa.gov/applications/, accessed September 22, 2011.

[6]See http://smap.jpl.nasa.gov/files/smap2/Apps_Plan_110915.pdf.

[7]See http://smap.jpl.nasa.gov/files/smap2/Workshop_Report_100309_final.pdf and http://smap.jpl.nasa.gov/files/smap2/Workshop_Report_final_21.pdf.

[8]A high-level summary of SMAP applications areas, with links to related and partner programs, is available at http://smap.jpl.nasa.gov/applications/.

[9]See http://smap.jpl.nasa.gov/files/smap2/Apps_Plan_110915.pdf.

[10]SMAP's list of official early adopters can be found at http://smap.jpl.nasa.gov/files/smap2/ SMAP%20EA.pdf.

[11]In light of the numerous applications that DESDynI can address, NASA convened a workshop in October 2008 to discuss these applications and related data products; the workshop report is available at http://desdyni.jpl.nasa.gov/files/DESDynI%20Applications%20Report%20V1.0.pdf. The 2010 HyspIRI Science Symposium on Ecosystem Data Products included a focus on terrestrial ecosystems and agriculture to "identify potential higher level products for end users." The 2011 HyspIRI Science Symposium on products for ecosystems and climate includes as foci the questions "What are the 10 highest priority products for climate and societal benefit?" and "How will they uniquely support NASA science and application goals?" HyspIRI has USDA, NOAA, and USGS representatives as well as applied researchers on the science study group. GEO-CAPE has had significant representation by applications-oriented people at the mission definition workshops and on the science definition teams. The air quality management community has been especially active and involved in the mission definition, including an Environmental Protection Agency air quality manager on the Science Definition Team. It is notable that ESD scheduled the second GEO-CAPE community workshop (May 2011) to occur in coordination with the Environmental Protection Agency's Satellite and Above-Boundary Layer Observations for Air Quality Management workshop and NASA's Air Quality Applied Science Team meeting.

are available in the program's annual reports. Among additional activities in 2010, the Applied Sciences Program initiated new external research to improve measurement of the societal benefits associated with Earth science information, for example, the economic value of Earth science data products in drought monitoring for index insurance and the cost-savings enabled by observations that facilitate more efficient monitoring of air and water pollution.[29] Looking ahead, the Applied Sciences Program description that accompanied the NASA FY2012 budget featured joint "solicitations with research and end-user organizations, contributions to mission science teams to ensure consideration and incorporation of applications requirements throughout the mission design process, and continuation of efforts to build skills and capabilities for

[29]A report on a 2010 workshop funded by the NASA Applied Sciences Program on benefit estimation methodology is M.K. Macauley and R. Laxminarayan, Valuing information: Methodological frontiers and new applications for realizing social benefits, *Space Policy* 26(4):249-251, 2010; an edited volume of the workshop papers is forthcoming (*The Value of Information: Methodological Frontiers and New Applications,* R. Laxminarayan and M.K. Macauley, eds., Springer).

accessing and applying Earth observations data to benefit society."[30] NOAA is also partnering with NASA to address societal applications of decadal survey-recommended missions (Box 2.3).

Although this committee has not reviewed the Applied Sciences Program in detail, it notes that NASA's Applied Sciences Advisory Group (ASAG) concluded recently that the program was understaffed and financially challenged considering the breadth of societal benefit areas it needs to address.[31] In its 2010 Annual Report,[32] the Applied Sciences Program noted in the section titled "Setting Priorities" that "based on an analysis of financial and personnel resources, the Program concluded that it could not pursue all nine [applications areas of the U.S. Group on Earth Observations] effectively… [and] made a difficult decision to emphasize only a sub-set of these." As a result, it selected four applications areas of the nine, recognizing "that there are important applications that may not be pursued, and there are societal benefits that will not be realized." However, specifically with respect to the decadal survey-recommended new starts, the committee found as follows:

Finding: Aligned with the intent of the 2007 decadal survey, NASA's Applied Sciences Program has begun to engage applied researchers and governmental (federal and state) operational users on some survey mission science definition and applications teams and to conduct research to better understand the value of these applications.

SUBORBITAL PROGRAM

NASA's suborbital program supports Earth science orbital missions (EOS, A-Train, and decadal survey missions) in the areas of field science, algorithm development, instrument test, and satellite calibration and validation and helps develop the next generation of satellite instruments. The program was in decline from FY1999 through FY2007 and, as recommended in the 2007 survey, ESD has expanded its financial support of its Airborne Science Program by almost a factor of 2, with an increase in total flight hours by a factor of 2.5. The flight hours associated with decadal survey-recommended missions doubled from FY2006 to FY2011 (Figure 2.2). Growth in airborne mission frequency, duration, and maturity is particularly evident at the NASA Ames Research Center Earth Science Project Office (ESPO).[33]

The successes and improved return on investment brought about through the use of airborne simulators such as the MODIS Airborne Simulator (MAS)[34] and the MODIS/ASTER (MASTER) airborne simulator[35] show that missions will benefit the most when they plan in advance for the use of airborne measurements for instrument flight test and algorithm development before launch and for calibration of instruments and algorithm validation measurements post-launch.

Two Global Hawk uninhabited aerial vehicles (UAVs) were added to the research fleet, vastly expanding the long-duration, heavy-lift, high-altitude capabilities available to NASA scientists.[36] The first Global

[30]NASA, "Earth Science," in the "FY 2012 Budget Estimate by Section," available at http://www.nasa.gov/news/budget/2012.html, p. ES-87.

[31]Ray Hoff, chair of the NASA ASAG, cited on p. 8 of "Meeting Minutes," from the October 10, 2010, meeting of the NASA ASAG. Available at http://science.nasa.gov/media/medialibrary/2011/01/06/FinalASAGMeetingMinutesOctober2010-1_TAGGED.pdf.

[32]NASA, *2010 Annual Report, NASA Earth Science Applied Sciences Program,* NP-2011-08-764-HQ, available at http://appliedsciences.nasa.gov/pdf/2010_NASA_ASP_Annual_Report_v14_150dpi.pdf, p. 40.

[33]M. Freilich, Director, Earth Science Division, NASA, presentation to the Committee on the Assessment of NASA's Earth Science Program, April 27, 2011.

[34]See http://mas.arc.nasa.gov/.

[35]See http://master.jpl.nasa.gov/.

[36]J.C. Naftel, *NASA Global Hawk: A New Tool for Earth Science Research,* NASA Technical Manual 2009-214647, H-2951, DFRC-960, NASA Dryden Flight Research Center, Edwards, Calif., May 2009.

BOX 2.3 NASA-NOAA RESEARCH AND APPLICATIONS PARTNERSHIP

The 2007 decadal survey charge specifically directed the committee to "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."[1] There are clear demonstrated linkages between NASA's Earth science observations from foundational NASA missions and the application of their data and information to address societal needs by NOAA; these linkages exist for every survey mission and for each of NOAA's four long-term goals.[2] NOAA's National Environmental Satellite Data and Information Service has identified an applications point of contact for every survey-recommended mission. On the Soil Moisture Active-Passive (SMAP) mission, NOAA staff has participated in all workshops, and NOAA has identified an early adopter to focus on the "transition of NASA SMAP research products to NOAA operational numerical weather and seasonal climate predictions and research hydrological forecasts."[3]

[1]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007, p. 383.

[2]NOAA's four long-term goals are the following: (1) climate adaptation and mitigation: an informed society anticipating and responding to a changing climate and its impacts; (2) weather-ready nation: society prepares for and responds to weather-related events; (3) sustainable ocean ecosystems: marine fisheries, habitats, and biodiversity sustained within healthy and productive ecosystems; and (4) sustainable coastal communities: coastal and Great Lakes communities that are environmentally and economically sustainable.

[3]See http://smap.jpl.nasa.gov/files/smap2/2011%20SMAP%20Early%20Adopters%20List1.pdf.

INTEX-B	2006
CC-VEX	2006
Arctic Sea Ice	2006
INTEX-B	2006
MILAGRO	2006
WRAP	2006-2009
Arctic Ice 2007	2007
CLASIC	2007
TC-4	2007
ARCTAS	2008
Calipso Caribean	2008
CASIE	2009
ASCENDS test flights	2009
Racoro	2009
GloPac	2010
ABACATE	2010
GLEAM	2010
ASCENDS test flights	2010
AID for ASCENDS	2010
SIMPL	2010
MACPEX	2011
CAR	2011
4Star	2012
DC-3	2012
HEX	2012
SEAC4RS	2012
AVIRIS CONUS	2006-2012
UAVSAR	2006-2012
CLPX II	2007-2008
SMAPVEX	2008, 2010-11
OIB	2009-2015
Earth Venture 1	2011-2014

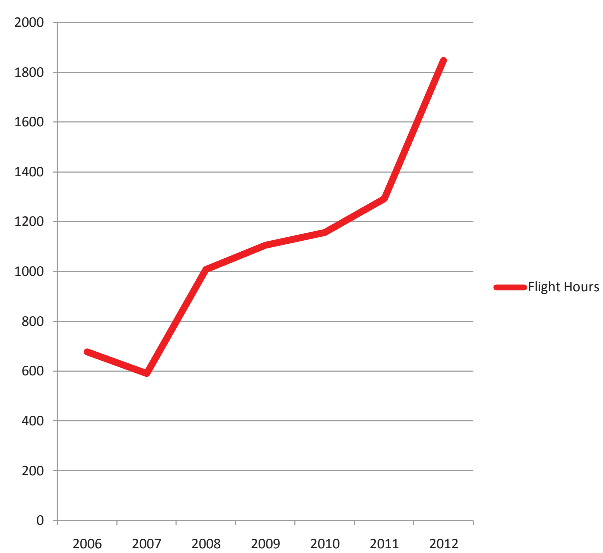

FIGURE 2.2 Airborne Science Program flight hours in support of decadal survey missions, 2006-2011. SOURCE: Courtesy of NASA.

Hawk science mission in 2010 was a joint NOAA/NASA project measuring gases and aerosols in the upper troposphere and lower stratosphere and included satellite validation; the second was a NASA mission that focused on hurricane development; and the next NOAA mission targeted observations designed to improve operational weather forecasts and evaluated an automated dropsonde system. The Global Hawk will be used in two upcoming Earth Venture missions—the Airborne Tropical Tropopause Experiment and the Hurricane and Severe Storm Sentinel.

Suborbital missions are also used as a testbed for future spaceborne technology to obtain complementary data that are not amenable to spaceborne observation, for validation of satellite instruments, and for scientific process studies. A unique suborbital program is IceBridge, with regular campaigns in the Arctic and Antarctic to span the gap between the demise of ICESat and the launch of ICESat-2 and provide calibration/validation for those missions (Box 2.4). Suborbital missions cannot, however, be used as a substitute for the many spaceborne missions that require global coverage.

ESD has used airborne platforms for development of instruments for survey missions, at the same time providing science and application results. For example, the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR),[37] a reconfigurable, polarimetric L-band synthetic aperture radar (SAR), was developed in support of the DESDynI mission. The UAVSAR observed ground deformation that provided new constraints on fault rupture and stress redistribution following the earthquake in Baja California in April 2010. The UAVSAR also imaged the coastline from Florida to Texas after the 2011 Gulf of Mexico oil spill, as well as collecting data over the open ocean.

The DISCOVER-AQ (Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality) campaign in July 2011 is another example of NASA's successful use of airborne platforms. The DISCOVER-AQ campaign used NASA's P-3B and UC 12 aircraft equipped with in situ and remote sensors to make observations of atmospheric composition between Baltimore, Maryland, and Washington, D.C., in July 2011. The goal of this Earth Venture airborne program is to improve interpretation of satellite observations, which have low vertical resolution or are total-column measurements, so that they can be used to observe and characterize surface air quality. Four phases are planned in different polluted regions. The profile data from DISCOVER-AQ are also important for the development of instruments on the GEO-CAPE decadal survey mission, and they provide complementary data not available from space for process studies of air pollution.

Other successful airborne science efforts include the Student Airborne Research Program (a hands-on 6-week summer course in airborne science for undergraduate and graduate students); the Midlatitude Airborne Cirrus Properties Experiment (MAPEX) for investigating cirrus cloud properties and their effect on Earth's radiation balance); and the Genesis and Rapid Intensification Process (GRIP), which examines the development of tropical storms and their transition to hurricanes.

> **Finding:** The suborbital program, and in particular the Airborne Science Program, is highly synergistic with upcoming Earth science satellite missions and is being well implemented. NASA has fulfilled the recommendation of the decadal survey to enhance the program.

[37]See http://uavsar.jpl.nasa.gov.

TECHNOLOGY DEVELOPMENT

The NASA Earth Science Technology Office (ESTO[38]) is the office within ESD that has responsibility for promoting the development of technology required to make the decadal survey missions flight ready.[39] Technology development is part of a broader category that NASA and the 2010 National Research Council report *An Enabling Foundation for NASA's Space and Earth Science Missions*[40] consider "mission enabling." Following release of the 2007 decadal survey, ESTO explicitly tailored its solicitations toward advancing survey priorities and has funded more than 70 new, competitively selected projects that support the survey missions to varying degrees.[41] ESTO has made investments in both mission-focused and crosscutting technologies intended to reduce the technical risk associated with implementing the decadal survey-recommended missions (Figure 2.3).

The most recent Research Opportunities in Space and Earth Sciences (ROSES) Advanced Information Systems Technology (AIST) solicitation (August 2011) partners with ESD's Applied Sciences Program and makes direct mention of the 2007 survey as a primary document that identifies "the relevant missions and programs and supporting technologies for this solicitation…." It also notes that "the Tier 3 decadal survey missions not yet in study phase are also relevant to AIST."[42]

Finding: ESTO has organized its proposal solicitations around the 2007 decadal survey and is investing to advance technological readiness across the survey mission queue.

RESEARCH AND ANALYSIS

The 2007 decadal survey made specific recommendations with respect to mission-enabling research activities that aim to create new knowledge and develop a technically and scientifically capable workforce. One part of this broader mission-enabling category is research and analysis (R&A) (also see the section above, "Technology Development"). The survey recommended that NASA ensure that its support for R&A continue at a level commensurate with its ongoing and planned missions, with investments being made both along individual mission lines and across the mission portfolio. It further recommended that this investment remain protected from use to cover cost growth in missions.[43] The 2010 NRC report *An Enabling Foundation for NASA's Space and Earth Sciences Missions*[44] identified that ESD allocated about 40 percent of its budget to the broad category of mission-enabling activities, and NASA has reaffirmed the

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[38]Information about ESTO is available at http://esto.nasa.gov/.

[39]ESTO also interacts with the NASA Research and Analysis program through joint monitoring of research projects funded under programs like REASoN (Research, Education and Applications Solutions Network; see http://earthdata.nasa.gov/our-community/community-data-system-programs/reason-projects) and MEaSUREs (Making Earth Science Data Records for Use in Research Environments; see http://earthdata.nasa.gov/our-community/community-data-system-programs/measures-projects) that are aimed at advancing data management protocols that have implications for new missions.

[40]National Research Council, *An Enabling Foundation for NASA's Space and Earth Science Missions,* The National Academies Press, Washington, D.C., 2010.

[41]M. Freilich, Director, Earth Science Division, NASA, presentation to the Committee on the Assessment of NASA's Earth Science Program, April 27, 2011.

[42]NASA Science Mission Directorate, "Advanced Information Systems Technology," Research Opportunities in Space and Earth Sciences–2011, NASA Research Announcement, Solicitation NNH11ZDA001N-AIST, released February 18, 2011, available at http://nspires.nasaprs.com/external/, pp. A.41-2 and A.41-3.

[43]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 15.

[44]National Research Council, *An Enabling Foundation for NASA's Space and Earth Science Missions,* 2010.

BOX 2.4 ICEBRIDGE: A SUBORBITAL SUCCESS STORY

IceBridge is a 6-year, $90 million airborne effort intended to partially fill the gap between ICESat and ICESat-2, serving in a calibration/validation role to improve the utility of ICESat measurements and link them to CryoSat-2 (Figure 2.4.1). It will provide measurements of surface elevation change over parts of the ice sheets, Arctic glaciers, and sea ice.[1] A second objective is to measure properties needed by ice models, such as bed topography, ice thickness, and snow depth. The focus is on areas that are changing rapidly, such as the Arctic and Southern Ocean sea ice, outlet glaciers on the Greenland ice sheet, the Antarctic Peninsula, and southeast Alaska glaciers. Continued monitoring of elevations in the interior regions of ice sheets in Greenland, West Antarctica, and East Antarctica is also a priority. Logging more than 1,600 flight hours and 760,000 flight kilometers, IceBridge has also delivered key measurements that cannot be made by satellite, including ice thickness and surface elevations of the glacier tributaries feeding into the main Pine Island Glacier, Antarctica; the bathymetry of floating ice tongues and their thinning inland; and bedrock topography and ice thickness of fast-moving outlet glaciers in Greenland.

IceBridge measurements support and enhance complementary projects such as the Investigating the Cryospheric Evolution of the Central Antarctic Plate project; mapping the glacier bed and internal ice layers over areas of international ice core drilling projects in Greenland and Antarctica; and calibration for the European Space Agency's ice-observing satellite, CryoSat-2. IceBridge serves as an example of successful collaborations

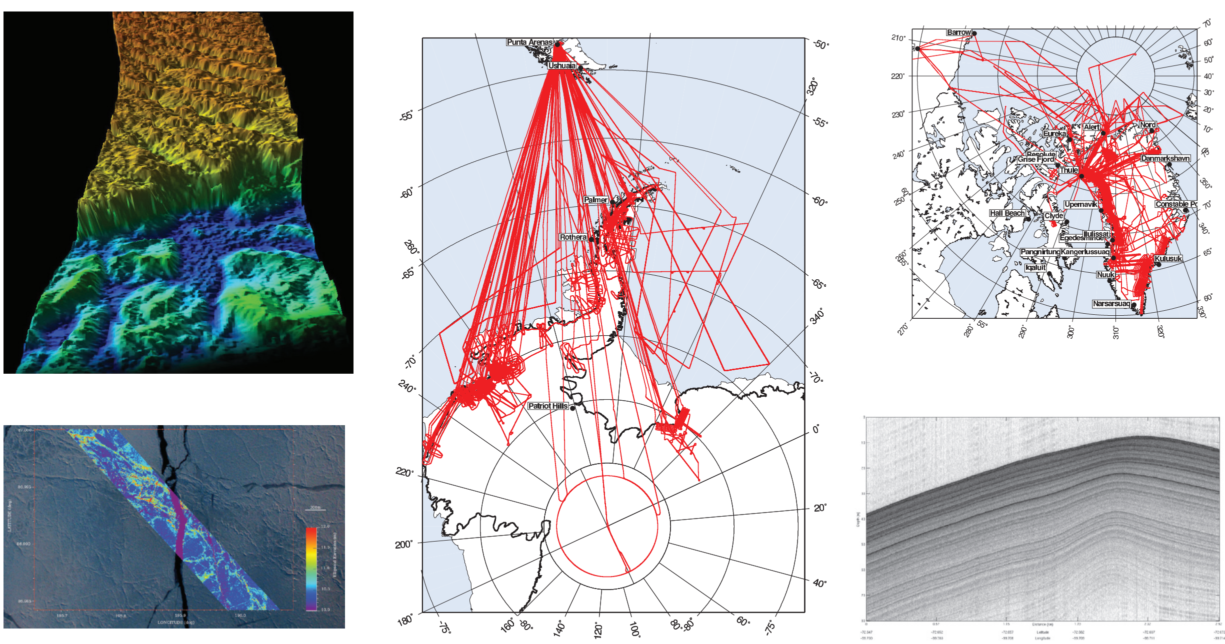

FIGURE 2.4.1 IceBridge provides spatially extensive key measurements in the Arctic and Antarctic in support of Earth science and instrument calibration. *Top left:* surface altimetry of Crane Glacier, Antarctica; *bottom left:* Arctic sea ice ellipsoid elevation from the Airborne Topographic Mapper in support of CryoSat-2 calibration; *center:* IceBridge flight lines over Antarctica; *top right:* IceBridge flight lines over Greenland; *bottom right:* snow radar showing internal layers of Pine Island Glacier, Antarctica. SOURCE: *Top left:* Courtesy of Kyle Krabill and the NASA Airborne Topographic Mapper Team; *bottom left:* Courtesy of the NASA Airborne Topographic Mapper Project; *center and top right:* Courtesy of NASA Operation IceBridge; *bottom right:* Courtesy of the Center for Remote Sensing of Ice Sheets.

involving more than a dozen U.S. universities and international collaborations with scientists from Australia, Canada, Denmark, France, Greenland, and the United Kingdom. All data are freely available within 6 months of acquisition through the National Snow and Ice Data Center.

Among the advantages of suborbital efforts like IceBridge are that varied and multiple instruments can be used onboard airborne laboratories, innovative instruments can be tested, and flight patterns can be optimized for specific tasks. However, suborbital platforms can provide observations only at regional scales. In this respect, IceBridge is an ideal example, as it was able to focus on especially sensitive portions of ice sheets and glaciers as its domain. Even in this context, however, it must leave unobserved large portions of the major ice sheets and sea ice, which ICESat-2 will regularly monitor over several years.

[1]The IceBridge instrument suite currently consists of three lidar systems (Airborne Topographic Mapper, Laser Vegetation Imaging Sensor, and Sigma Space Photon Counting Lidar Prototype), four radar systems (Multi-channel Coherent Depth Sounder, Snow depth radar, Ku-band radar altimeter, and accumulation radar), gravimeter, and high-resolution aerial photography. Platforms include NASA's airborne laboratories on the DC-8, P-3B, King Air B-200, the Basler BT-67, a Single Engine Otter, and UAVs, including NASA's Global Hawk and Ikhana (planned).

accuracy of this allocation for 2011, stating that funding for mission-enabling activities is just under half of ESD's total budget.[45]

Although there are specific NASA budget items titled "research and analysis," the committee was made aware by NASA officials that the level of integration of R&A activities throughout ESD, and the broad definition used for R&A, make it difficult to quantify the total investment in R&A with a specific number. Nevertheless, the committee concluded that the level of R&A and the manner in which R&A is conducted in ESD are commensurate with the recommendation and intent of the 2007 decadal survey. However, with cost growth in missions and with a lower overall budget, there will be continued pressure to reallocate R&A funds to meet mission needs.

The survey noted that assimilation of satellite data into numerical models, and model-based Observing System Simulation Experiments (OSSEs), are other facets of data integration warranting continued investment by NASA. It also recommended that NASA, NOAA, and the USGS should increase their support for Earth system modeling, including provision of high-performance computing facilities and support for scientists working in the areas of modeling and data assimilation.[46] Although significant progress has been made in the area of data assimilation for weather forecasts, much work remains to verify integrated Earth systems models. In particular, Earth observations have to be assimilated into such models to create a consistent and integrated picture of the Earth system, and these observations have to be integrated into a predictive modeling system that can make reliable forecasts far into the future.[47]

[45]M. Freilich, Director, Earth Science Division, NASA, presentation to the Committee on the Assessment of NASA's Earth Science Program, April 27, 2011.

[46]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 15.

[47]The 2007 decadal survey also discusses the need for data to be acquired and archived in a way that supports future reprocessing, noting its particular importance for the development of climate data records. As stated by the decadal survey's Panel on Climate Variability and Change: "Reprocessing of data allows the incorporation of gains in knowledge, the correction of errors in preflight and in-flight calibrations, inclusion of changes in instrument function, and the correction of errors in earlier processing algorithms" (National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 264). For a more detailed discussion of reprocessing and its role in a climate observing system, see K. Trenberth, "The important

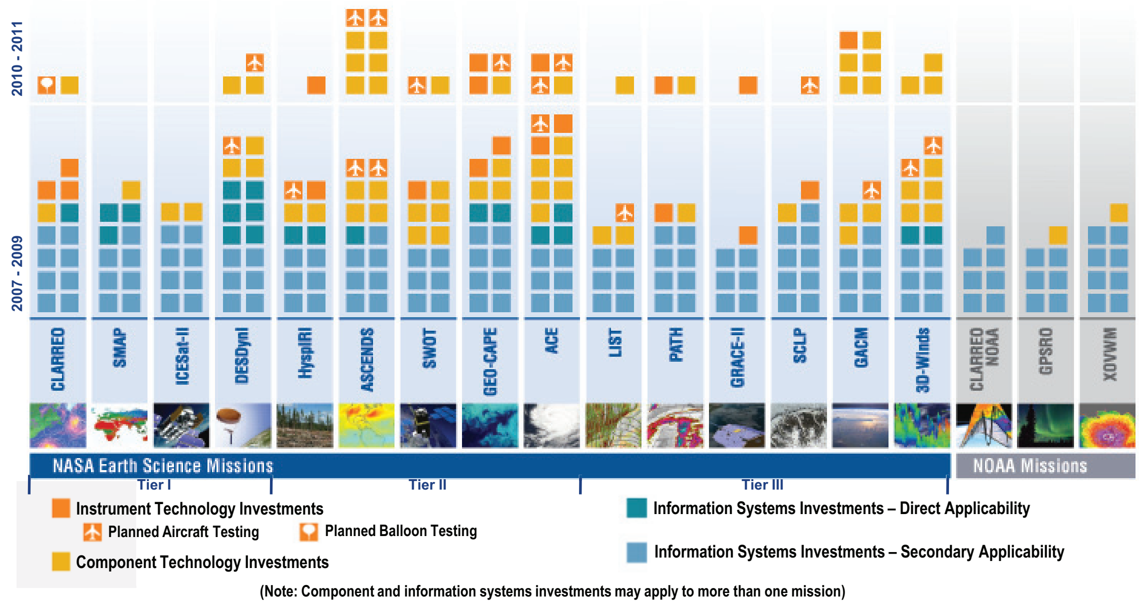

FIGURE 2.3 Investments made by the Earth Science Technology Office in technologies for decadal survey missions. Investments are divided into four categories: instrument technology investments, component technology investments, information systems investments-direct applicability, and information systems investments-secondary applicability. Component and information systems investments may apply to more than one mission. Each box represents a single investment or test. SOURCE: NASA Earth Science Technology Office.

The committee's overall assessment is as follows:

Finding: NASA has maintained a healthy investment in R&A activities and has protected the budgets of both mission-specific and non-mission-specific R&A programs against possible reallocation to cover cost growth in mission hardware.

role of continuity of observations and data products for IPCC: Critical role for GCOS and WCRP," GEOSS Support for IPCC Assessments, A Workshop on the Data Needs of the Climate Impacts, Adaptation and Vulnerability Research Community, February 1-4, 2011, Geneva, Switzerland, meeting documents and presentations available at http://www.earthobservations.org/meet_wss.shtml.

3

Challenges to Implementation of Decadal Survey Priorities

The 2005 interim report of the Earth science and applications from space decadal survey discussed the importance of the U.S. civilian Earth observing system of environmental satellites and warned, "Today, this system of environmental satellites is at risk of collapse."[1] It went on to list a number of canceled, descoped, or delayed Earth observation missions. The release of the decadal survey in early 2007 and a positive response to the recommendations by the administration and Congress generated optimism that the threatened collapse might be averted. However, the loss of the Orbiting Carbon Observatory (OCO) and Glory; the combination of increased cost estimates for the survey-recommended missions and the failure of Congress to provide NASA the necessary budget increases to implement the recommended missions; the impact to the National Oceanic and Atmospheric Administration (NOAA) as it absorbs massive cost increases in developing its next-generation polar programs; and a U.S. budget for discretionary spending that appears highly constrained for the foreseeable future have resulted in an austere outlook for Earth observations over at least the next decade. The present trends point to the feared degradation of the U.S. observing system from space that was warned by the 2005 interim report.

EARTH SCIENCE DIVISION BUDGETS

The budget history of NASA's Earth Science Division (ESD), translated into constant fiscal year (FY) 2006 dollars (the year the survey was completed), illustrates the difficulty in realizing the recommendations of the decadal survey (Figure 3.1). From FY1996 through FY2001 the budget remained approximately constant at about $2 billion. Beginning in FY2002, the budget declined steadily, reaching a minimum of about $1.3 billion in FY2007, a 46 percent decrease. The 2007 survey recommended that the NASA Earth science budget be returned to the FY2002 level of $2 billion in annual funding (in FY2006 dollars) to support the

[1]National Research Council, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation,* The National Academies Press, Washington, D.C., 2005, p. 2.

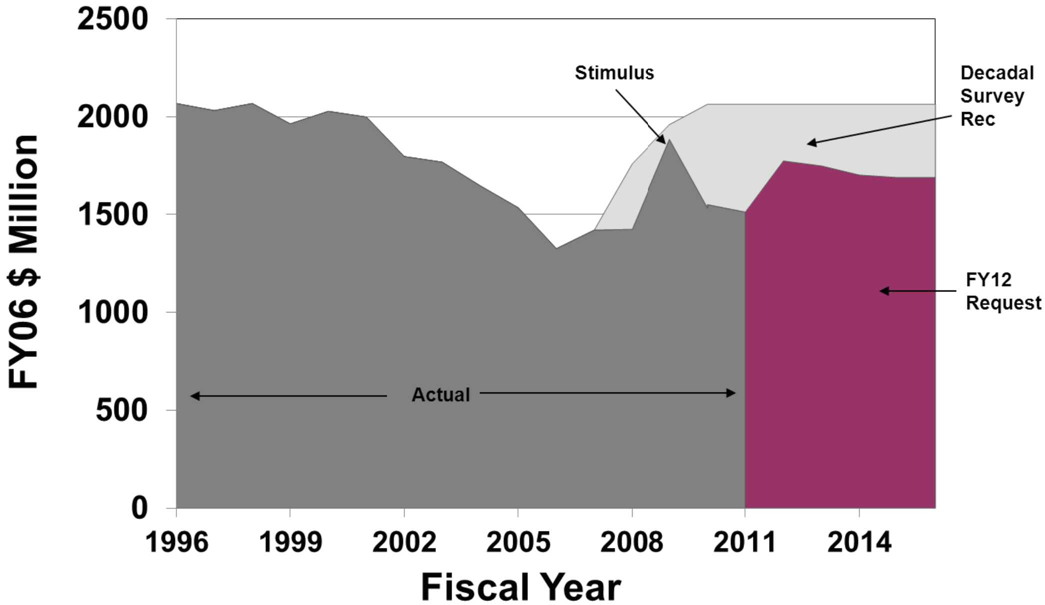

FIGURE 3.1 NASA Earth Science Division budget from fiscal year (FY) 1996 to FY2011 (actual) and projections out to FY2016, based on the President's FY2012 budget request in constant FY2006 year dollars, as compared to the 2007 decadal survey recommendation. SOURCE: NASA budget data from Michael Freilich, Director, NASA Earth Science Division, "Earth Science Division Decadal Survey Status," presentation to the Committee on the Assessment of NASA's Earth Science Program, April 27, 2011.

missions and related programs set forth in the survey.[2] The favorable response to the decadal survey by the administration and Congress and passage of the American Recovery and Reinvestment Act of 2009 reversed this decline. However, budget stalemates in FY2010 and FY2011 and an austere forward-looking FY2012 request have resulted in ESD being funded at less than the $1.5 billion level for the foreseeable future, far below what the survey recommended (see Figure 3.1). This failure to restore the Earth science budget to a $2 billion (FY2006) level, as recommended by the survey, is the primary reason for the inability of NASA to realize the mission launch cadence recommended by the survey. Increases in scope directed by Congress and the administration (e.g., the addition of the $150 million Thermal Infrared Sensor on the Landsat Data Continuity Mission and the establishment of the Climate Continuity missions[3]) without the commensurate required funding, further strained an already-limited ESD budget. This constraint was compounded by the need for an OCO mission and the decision to build its replacement following the 2009 launch vehicle failure.

The resulting delay in implementing the planned and recommended Earth observation missions, coupled with the currently predicted mission end dates for many operating missions, has led to a projected rapid net decrease in total NASA Earth science missions. Figure 3.2 is an updated version of a similar chart of mission and instrument trends that was produced by the 2007 decadal survey. Using agency estimates

[2]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

[3]The Climate Continuity missions include SAGE-III (2015), OCO-3 (2015), GRACE-FO (2016), and PACE (2019-2020).

for the anticipated remaining lifetime of in-orbit missions and counting new missions only if they have been formally approved in enacted agency budgets, indicates that the number of missions could decline from 23 in 2012 to only 6 in 2020, and the number of NASA and NOAA Earth-observing instruments in space could decline from a peak of about 110 in 2011 to approximately 20 in 2020. A more optimistic scenario based on the Climate-Centric Architecture put forth to leverage anticipated augmented funding to support administration priorities is also shown in Figure 3.2; however, this plan, which has not been fully funded, also projects a precipitous decline in observing capabilities.

The mission and instrument trends illustrated in Figure 3.2 warn of a coming crisis in Earth observations from space, in which our ability to observe and understand the Earth system will decline just as Earth observations are critically needed to underpin important decisions facing our nation and the world. Advances in weather forecast accuracy may slow or even reverse, and gaps in time series of climate and other critical Earth observations are almost certain to occur.[4] When these long-running data streams fall silent, users requiring these observations will go unsupported, and progress toward understanding the Earth system and how it supports life may stagnate. The committee recognizes that the number of missions and instruments in orbit is only one indicator of program health, given that some of the newer instruments measure multiple geophysical parameters. Yet even with the very capable instruments in NASA's and NOAA's current pipelines, the overall loss of capability will be felt by the entire Earth science community, and it will have a stark impact on certain specific disciplines.[5] While opportunities for international collaboration may help to partially mitigate this loss in capability (see in Chapter 4 the section "International Partnerships"), reliance on such partnerships also carries risks. Moreover, foreign partners are not immune to the challenges currently faced by the U.S. Earth science program, as evidenced by the European Space Agency's threat to not launch its Sentinel satellites unless it receives the funding to keep them operational beyond 2014.[6]

The committee is concerned that overruns in other NASA science divisions might begin to further impact the already stressed NASA Earth science budget. Just as the research and analysis program funds are fenced off from other aspects of the NASA Earth science budget to prevent Earth science mission overruns from threatening the overall health of the program, so also the committee hopes that NASA's Earth science program can be protected from overruns by non-Earth science missions. The committee was encouraged to learn that NASA will not cover overruns in other divisions of the agency with money from the Earth Science Division budget in FY2012.[7]

> **Finding:** Funding for NASA's Earth science program has not been restored to the $2 billion per year (in FY2006 dollars) level needed to execute the 2007 decadal survey's recommended program. Congress's failure to restore the Earth science budget to a $2 billion level is a principal reason for NASA's inability to realize the mission launch cadence recommended by the survey.

> **Finding:** The nation's Earth observing system is beginning a rapid decline in capability as long-running missions end and key new missions are delayed, lost, or canceled.

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[4]See, for example, Office of the Inspector General, *Audit of the Joint Polar Satellite System: Challenges Must Be Met to Minimize Gaps in Polar Environmental Satellite Data,* Final Report No. OIG-11-034-A, September 30, 2011, available at http://www.oig.doc.gov/Pages/Audit-of-the-Joint-Polar-Satellite-System.aspx.

[5]There is as yet no plan to replace the capabilities of the Aura satellite, for example, which has served as a primary data source for the atmospheric chemistry community. Issues of data continuity and the lack of a comprehensive plan for stewardship of such sustained observations are discussed in Chapter 4.

[6]P.B. de Selding, ESA's Dordain restates Sentinel launch cancellation threat, *Space News,* January 12, 2012, available at http://www.spacenews.com/earth_observation/120112-dordain-cancel-sentinel.html.

[7]D. Leone, NASA's science, cross-agency budgets take a hit to pay for Webb, *Space News,* September 22, 2011, available at http://www.spacenews.com/civil/110922-science-cross-agency-budgets-take-hit.html.

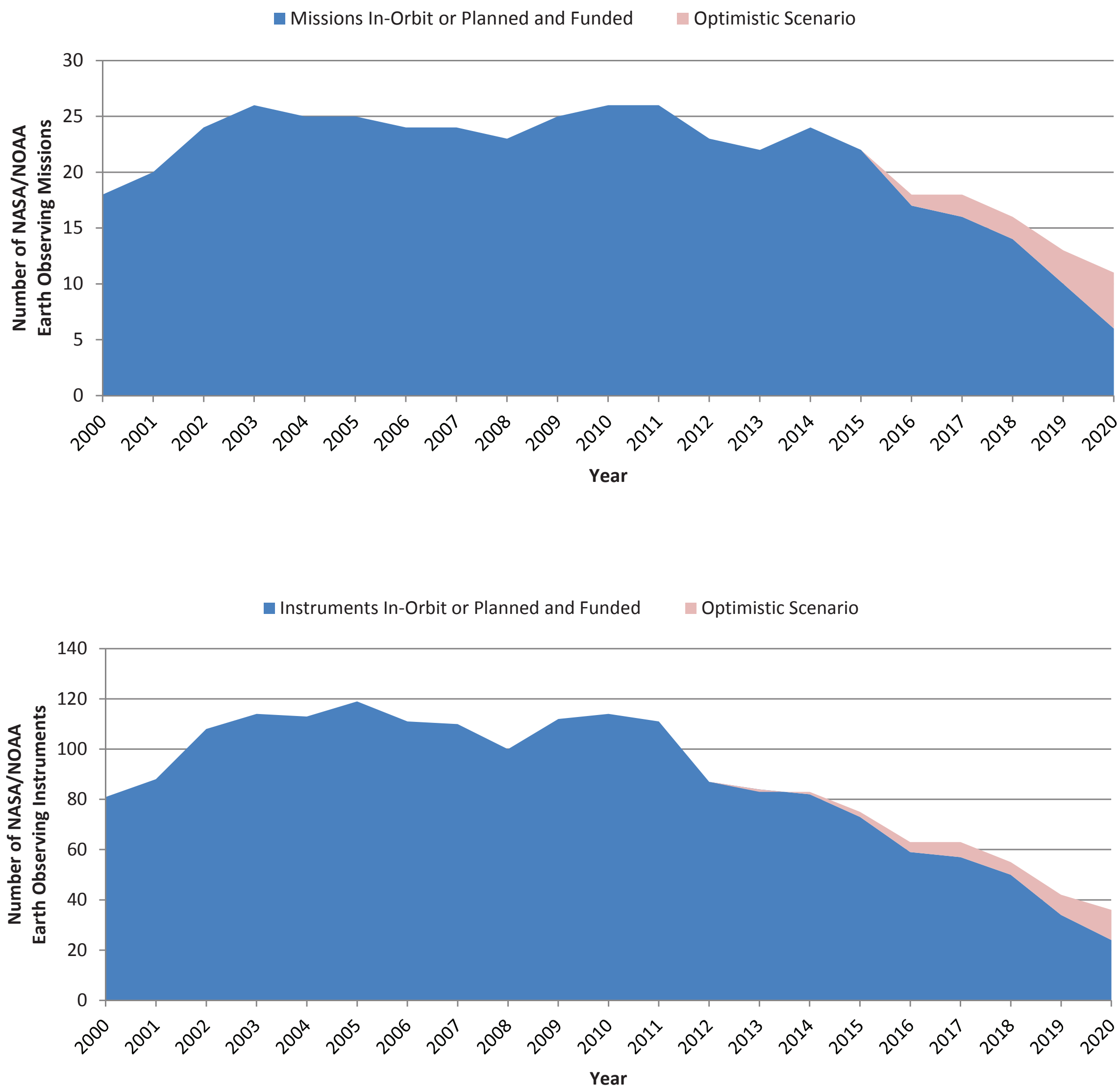

FIGURE 3.2 Number of operating (2000-2011) and planned (2012-2020) NASA and NOAA Earth observing missions (*top*) and instruments (*bottom*). Shown in blue are missions that are funded and have a specified launch date in NASA or NOAA budget submissions. Thus, the blue curve does not count missions (and associated instruments) that have been proposed or planned but are not yet funded or selected. Shown in pink is an "optimistic scenario" based on the Climate-Centric Architecture put forth to leverage anticipated augmented funding to support administration priorities that makes the following assumptions: GRACE-FO launches in 2016, PACE launches in 2019, ASCENDS launches in 2020, SWOT launches in 2020, EV-2 launches in 2017, SAGE-3 instrument launches in 2014, OCO-3 instrument launches in 2015, and EV-I instruments are launched every year starting in 2017 (plans are for EV-I instruments to be delivered for integration yearly; this assumes they also launch yearly). NOTE: Mission lifetimes for on-orbit missions are taken from estimates provided by NASA and NOAA; the NASA estimates are based on mission team estimates of remaining mission lifetime as provided (and reviewed by the Technical Panel) during the Senior Review process. Acronyms are defined in Appendix G. SOURCE: NASA and NOAA data.

COST GROWTH

The decadal survey included rough cost estimates for each of the recommended missions based on a simple parametric model as described in Box 2.3 of the 2007 decadal survey report.[8] These estimates were not based on extensive trade studies or detailed designs, although they were used as part of the process to determine the recommended timing of missions. As the first four missions moved toward implementation, however, estimated costs[9] grew a great deal for every mission, and this cost growth has contributed to the delay and deferral of missions.

Since the release of the survey, much discussion has focused on how "low" these estimates appear when compared with subsequent estimates for the missions prepared by formulation teams, leading to calls for independent cost estimates in future decadal surveys. *This response, to a large extent, misses the point.* It should not be surprising that a parametric estimate differs from more detailed cost estimates, nor is it surprising that there is not a statistical spread whereby some estimates are higher and some lower. There were differences in estimate content (e.g., decadal survey costs excluded R&A), changes in bookkeeping (e.g., NASA's change to budgeting to 70 percent confidence[10]), changes in scope (e.g., changes in mission lifetime and/or technology from that described in the decadal survey[11]), in-sourcing work (e.g., the SMAP spacecraft) from contractors to NASA center staff,[12] use of "directed" missions rather than competed "principal investigator-class" missions,[13] and increases in launch vehicle costs which drove the estimates further apart. Indeed, the implementation teams used the rough cost estimates in the survey as a starting point and were not initially directed to operate under a "cost cap" instruction. Starting with a higher ("more conservative") rough cost estimate might thus only have led to even higher subsequent estimates by changing the starting point from which the teams began studies of trade-offs for design formulation. See in Chapter 4 the discussion "Establishing and Managing Mission Costs" for potential solutions and strategies for dealing with the challenge of cost growth.

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[8]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 43.

[9]Cost estimates for missions not yet in implementation are considered unofficial, given that a mission (per NASA) does not have a formal and accepted cost estimate until a cost and scope are formally agreed to at the Mission Concept Review (MCR). Only SMAP and ICESat-2 currently have official cost estimates. Nevertheless, the unofficial cost estimates for CLARREO and DESDynI remain considerably above the decadal survey's rough estimate.

[10]This change is discussed in some detail in National Research Council, *Controlling Cost Growth of NASA Earth and Space Science Missions,* The National Academies Press, Washington, D.C., 2010.

[11]NASA established mission concept study teams for each of the missions; however, these teams were not given firm constraints in cost or scope from the outset, and many expanded on the concepts as set forth in the final set of recommended missions. The ESD director, during the committee's first meeting on April 28, 2011, suggested that this might have been exacerbated by teams using panel chapters (Part III of the document) rather than the consensus report (Parts I and II) to support a growth in scope. However, it is clearly noted in the decadal survey preface that the recommended missions represented a compromise across panels and intentionally did not include all of the instrument and spacecraft characteristics advocated by any particular panel in order to "maximize science and application returns across the panels while keeping with in a more affordable budget" (p. xvi). The report also warned against "requirements creep" and consequent damaging cost growth (see Box 2.3 in National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007).

[12]NASA has chosen to implement the preponderance of missions thus far via direct assignment to its centers. Indeed, NASA requires a certain number of in-house missions to maintain overall agency and center health. In-house missions allow for more direct control of mission implementation (aka "directed missions") compared with fully competed missions, although directed missions are also subject to a greater degree of oversight and programmatic and institutional requirements, which tend to drive cost upward.

[13]Competed missions arguably can be more efficient; however, they also tend to be driven by a small disciplinary-focused group with tightly focused requirements and capabilities and can be difficult to modulate and balance in the context of a mission portfolio after they have been selected through a proposal process.

Finding: Decadal survey missions have not been managed with sufficient consideration of the scope and cost provided by the decadal survey in an absolute or relative sense.

ACCESS TO SPACE

NASA procures launch services primarily through the NASA Launch Services (NLS) contract. The latest NLS contract, NLS II, was announced on September 16, 2010, and includes launch vehicle offerings from four vendors.[14] The Boeing Delta II launch vehicle, long a workhorse for launching NASA science missions, is being phased out and is currently not part of the NLS II contract.[15] (See Box 3.1 for more on Delta II.) Of the launch vehicles available through NLS II, only three are in current production (the Pegasus, Taurus, and Atlas V), only one (the Atlas V) meets or exceeds Delta II-class capability, and prices have dramatically increased. While some smaller-class launch vehicles are in development (e.g., Falcon 1 by Space Exploration Technologies and Athena by Lockheed Martin Space Systems), the only currently produced commercial medium-class launch vehicle on the NLS II contract, the Taurus, has failed in three of its last four launch attempts (the 2001 QuikTOMS, 2009 Orbiting Carbon Observatory, and 2011 Glory missions—all NASA Earth science missions). Given the current selection of launch vehicle options on NLS II, NASA Earth science missions are driven to either fit within the Pegasus/Taurus envelope (mindful of the recent history of the Taurus) or accommodate the excess performance and associated cost of the Atlas V.[16]

Compounding this situation, there is increased commercial sector emphasis on higher-performance launch vehicles, with commensurate higher prices, which at present has resulted in fewer opportunities for NASA Earth science missions to obtain access to space. Decreasing launch rates exacerbate a tendency for missions in development to grow in size and complexity as longer development times, higher overall mission costs, and fewer overall missions increase community expectations for the few missions that do make it to space. This creates a feedback loop with increasing costs driving increasing expectations and decreasing risk tolerance, which can further increase costs. The decadal survey "tilted away" from larger missions precisely because of this threat to programmatic robustness and explicitly recommended smaller, lower-cost, and less complex missions; however, the push toward higher-capability launch vehicles is pulling the program in this undesirable direction.[17] Thus, the lack of reliable, affordable, and predictable access to space has become a key impediment to implementing NASA's Earth science program.

[14]See http://www.nasa.gov/home/hqnews/2010/sep/C10-053_Launch_Services_Contract.html.

[15]On September 30, 2011, very late in the development cycle of this report, NASA announced that it had modified the NLS contract to add access to the remaining five Delta II rockets. Although not a permanent "fix" for the long-term lack of a Delta II equivalent launch vehicle, this approach could help considerably in the short term, as long as the price is not prohibitive given that NASA is now a sole user of this service (see NASA Contract Release C11-044, September 30, 2011; see also Box 3.1).

[16]Excess capacity in both injected mass and volume in the Atlas V fairing suggests the possibility of shared launches if missions with compatible launch requirements can be found; however, an Atlas V dual launch remains in the concept stage, and it is unclear whether costs might be sufficiently reduced through launch vehicle sharing so as to be worth the added complexity and risk.

[17]From the 2007 decadal survey: "Prior [National Research Council] reports [*Issues in the Integration of Research and Operational Satellite Systems for Climate Research; Part I: Science and Design* and *Part II: Implementation*, National Academy Press, Washington D.C., both published in 2000] have concluded that ensuring a balance of facility-class (large), medium, and small missions is important for successful science, enabling a program that balances long-term methodical scientific pursuits with the ability to respond quickly to new discoveries, opportunities, and scientific priorities. A mix of mission sizes also promotes participation at multiple levels of the scientific community, from graduate students to senior scientists. The committee's recommended missions (Chapter 2) tilt away from facility-class implementations of large multi-instrumented platforms (such as EOS or NPOESS) toward smaller missions to increase programmatic robustness." (National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, pp. 75-76.)

BOX 3.1 DELTA II LAUNCH VEHICLE CLASS

The Boeing Delta II launch vehicle came into being in 1989 after the space shuttle *Challenger* accident, due to the realization that the space shuttle could not perform as the nation's only access to space. Since then, the Delta II has been a medium-class workhorse for launching NASA science missions, including NASA Earth science missions such as Radarsat, Landsat-7, EO-1, Jason-1, EOS Aqua and Aura, ICESat, CALIPSO/CloudSat, Jason-2, Aquarius, and NPP (the last currently planned usage of the Delta II). The Delta II has provided reliable, affordable, and predictable access to space for more than two decades.

The U.S. Air Force and NASA both used the Delta II with great success until a decision was made in the 1990s to move forward with the Air Force Evolved Expendable Launch Vehicle (EELV) program. The EELV program had as its goal making government launches more affordable and reliable, and it eventually resulted in the development of two new launch vehicles, the Boeing Delta IV and the Lockheed Martin Atlas V, both of which began service in 2002. Once the Delta IV/Atlas V launch vehicles were demonstrated to be reliable, the Air Force stopped using Delta IIs, leaving NASA as the sole government user of the Delta II. The price of the Delta II began to rise as NASA assumed the full responsibility for Delta II-related infrastructure costs. Eventually, NASA decided that it could not afford to maintain the capability to launch Delta IIs from both the East and the West coasts and had planned to stop using Delta IIs entirely. More recently, there have been ongoing discussions about NASA providing access to the last five remaining Delta IIs as a gap filler between the situation today, including recognition of the two recent Taurus XL failures carrying the NASA Earth science missions Orbiting Carbon Observatory and Glory, and where NASA expects to be 2 to 3 years from now after SpaceX's Falcon-9 and Orbital Sciences Corporation's Taurus II are certified in accordance with NASA requirements.

In the meantime, the assumed launch rate that had been used as the basis for the EELV program never materialized, and maintaining two distinct launch vehicle types became more and more expensive. Accordingly, in 2006, with the blessing of the Air Force, a new company, United Launch Alliance (ULA), was formed to seek appropriate areas of commonality between the two launch vehicle families, mainly in the areas of people and facilities. The objective of ULA was to streamline the approach to building these launch vehicles to achieve cost efficiencies so that two different launch vehicle types could still be available to cover the possibility of one of them being unavailable for technical reasons, to prevent the United States from having (temporarily) no access to space. However, an unintended consequence of this decision was that ULA currently has no viable competition in this size range to help hold its costs in check. Exacerbating this situation, recent decisions, such as canceling NASA's Constellation program, dropped the demand for RS-68 engines (planned to have been used in the Ares V launch vehicle and used for the Delta IV launch vehicle), thus raising the per unit cost, given the fixed cost of a liquid rocket motor industrial base.

ULA is actively looking for further cost efficiencies in its approach to maintaining a two-launch-vehicle capability under the EELV program, and the Air Force is also investigating ways to stabilize EELV costs.[1] Nonetheless, the Delta IV and the Atlas V have demonstrated a remarkable success record to date, providing reliable, though expensive, access to space.

[1]See http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=space&id=news/awst/2011/05/09/AW_05_09_2011_p26-318881.xml.

Finding: Lack of reliable, affordable, and predictable access to space has become a key impediment to implementing NASA's Earth science program. Furthermore, the lack of a medium-class launch vehicle threatens programmatic robustness.

Although increased competition is projected for the higher-performance launch vehicle segment (e.g., through development of the Taurus II and Falcon 9), plans to develop alternative small to medium-class launch vehicles appear less firm. Space Exploration Technologies has shifted emphasis away from development of its Falcon 1/1e offerings in favor of its Falcon 9;[18] indeed the publicly available launch manifest shows just one Falcon 1e launch in 2014, compared with 27 Falcon 9/F9 Dragon/Falcon Heavy launches through 2017.[19] Alternatively, Orbital Sciences is currently developing its Taurus II medium-class launch vehicle, but its first flight is not scheduled until early 2012.[20] Non-commercial vehicles (e.g., Minotaur) exist that are capable of launching Delta II-class payloads, but the Commercial Space Act of 1998[21] precludes their use without special dispensation. To use a Minotaur, the NASA administrator must obtain approval from the Secretary of Defense and certify to Congress that its use of a non-commercial launch vehicle will result in cost savings to the federal government, meet all mission requirements, and be consistent with international obligations of the United States. International launch vehicles (e.g., Ariane, H-II) are also widely available; however, their use would require a partnership arrangement with a foreign agency and no exchange of funds.

The need for reliable and affordable access to space is by no means new or unique to NASA's Earth science program. The recent loss of two NASA Earth science missions due to launch vehicle failures, however, underscores the urgency of addressing the need.

Recommendation: NASA should seek to ensure the availability of a highly reliable, affordable medium-class launch capability.

LACK OF A NATIONAL STRATEGY FOR ESTABLISHMENT AND MANAGEMENT OF EARTH OBSERVATIONS FROM SPACE

As stated in the 2007 decadal survey, "The committee is concerned that the nation's civil space institutions (including NASA, NOAA, and the USGS) are not adequately prepared to meet society's rapidly evolving Earth information needs. These institutions have responsibilities that are in many cases mismatched with their authorities and resources: institutional mandates are inconsistent with agency charters, budgets are not well matched to emerging needs, and shared responsibilities are supported inconsistently by mechanisms for cooperation. These are issues whose solutions will require action at high levels of the federal government."[22] This call for action is not new. For more than 10 years the National Research Council (NRC) has stated the importance of developing a national strategy to sustain long-term climate and environmental data sets.[23]

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[18]Production of the Falcon 1 was suspended in 2011; see http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=space&id=news/asd/2011/09/28/01.xml&headline=SpaceX%20Puts%20Falcon%201%20On%20Ice.

[19]See http://www.spacex.com/launch_manifest.php, accessed May 13, 2011.

[20]In late 2011, as this report was in review, Orbital Sciences Corporation changed the name of the Taurus II to "Antares."

[21]The Commercial Space Act of 1998 is available at http://www.nasa.gov/offices/ogc/commercial/CommercialSpaceActof1998.html; see Section 205, "Use of Excess Intercontinental Ballistic Missiles," regarding the use of the Minotaur.

[22]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 66.

[23]From the 1999 National Research Council letter report "Assessment of NASA's Plans for Post-2002 Earth Observing Missions": "No federal entity is currently the 'agent' for climate or longer-term observations and analyses, nor has the 'virtual agency' envisioned in the [U.S. Global Change Research Program] succeeded in this function. . . . The task group endorses NASA's call for a high-level process to develop a national policy to ensure that the long-term continuity and quality of key data sets required for global change research are not compromised in the process of merging research and operational data sets" (National Academy Press, Washington, D.C., April 8, p. 6). And from the 2008 National Research Council report *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring*: "A coherent, integrated, and

The government has not developed such a national strategy for obtaining and managing Earth observations from space. In an era of fiscal constraint, such a strategy is even more important. The fact that a strategy has not been developed in spite of the severity of the need speaks to the difficulty of the problem.[24] Recent developments further illustrate the importance of a comprehensive national strategy for Earth observations from space. These include:

- Cancellation of the NOAA-Air Force National Polar-orbiting Operational Environmental Satellite System (NPOESS) program and the initiation of the more modest Joint Polar Satellite System (JPSS) to meet civilian needs for weather and climate-related data;
- Launch vehicle failures resulting in the loss of the OCO and Glory satellites;
- Termination of plans for improved, or even continued, geosynchronous temperature and moisture soundings over the United States for severe weather "nowcasting" and forecasting; and
- Budget shortfalls and the inability of NOAA to transition demonstrably valuable research observations to operational status as in the case of ocean vector winds and Global Positioning System radio occultation, as well as to honor international commitments.

Numerous reports from the NRC[25] have documented the repeated attempts by the principal civilian satellite agencies (NASA, NOAA, and now the USGS) to establish a long-term observing system that meets both research needs and operational requirements. However, the fundamental differences between agency missions, budgeting processes, congressional oversight, and structure have resulted in a less-capable, suboptimal system that is prone to stove-piped requirements, critical data gaps, and missed opportunities. Moreover, understanding Earth-system processes requires high-quality measurements of many physical, chemical, and biological variables—sometimes over decadal time periods—as well as the ability to insert new technologies to improve data quality and to address emerging science requirements and the need to combine observations across multiple variables, disciplines, and observing systems. Any long-term observing system must be able to accommodate relatively frequent changes in technology and scientific understanding, compared to systems that are designed for more stable requirements.

The 2010 Government Accountability Office report *Environmental Satellites: Strategy Needed to Sustain Critical Climate and Space Weather Measurements*[26] is only the most recent analysis of these chal-

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viable long-term climate observation strategy should explicitly seek to balance the myriad science and applications objectives basic to serving the variety of climate data stakeholders. The program should, for example, consider the appropriate balance between (1) new sensors for technological innovation, (2) new observations for emerging science needs, (3) long-term sustainable science-grade environmental observations, and (4) measurements that improve support for decision making to enable more effective climate mitigation and adaptation regulations [NRC, "A Review of NASA's 2006 Draft Science Plan: Letter Report," The National Academies Press, Washington, D.C., 2006]. The various agencies have differing levels of expertise associated with each of these programmatic elements, and a long-term strategy should seek to capitalize on inherent organizational strengths where appropriate" (The National Academies Press, Washington, D.C., p. 73).

[24]The committee is aware of a preliminary plan set forth by the Office of Science and Technology Policy (http://www.whitehouse.gov/sites/default/files/microsites/ostp/ostp-usgeo-report-earth-obs.pdf). This plan, however, stops far short of identifying a workable architecture for provision of new and sustained Earth observations. The report acknowledges the challenge set forth in the 2007 decadal survey associated with provision of such measurements and outlines existing mechanisms to plan and prioritize measurements nationally and internationally; however, it does not establish, recommend, or fund a comprehensive strategy.

[25]*Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part I. Science and Design* (2000), *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (2000), *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations* (2003), *Extending the Effective Lifetimes of Earth Observing Research Missions* (2005), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (2007), and *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft* (2008); all National Research Council reports published by The National Academies Press, Washington, D.C.

[26]*Environmental Satellites: Strategy Needed to Sustain Critical Climate and Space Weather Measurements* (GAO-10-456, April

lenges. Many mechanisms have been developed to coordinate and implement a comprehensive, long-term observing system, such as the U.S. Global Change Research Program (USGCRP) and the U.S. Group on Earth Observations, but ultimately agencies must respond to short-term pressures and budget realities. Yet the observational component is by far the largest cost driver in the USGCRP. The numerous coordination mechanisms do not have sufficient standing to influence budgets and schedules. The result is thus a "patchwork" of missions and sensors, with little assurance that critical measurements will be continued for the long term or that new capabilities can be infused in a predictable manner.[27]

The USGCRP (and the program in its form as the Climate Change Science Program during the George W. Bush Administration) is one model for providing this coordination and leadership, but its effectiveness is not sufficient for the long development and implementation time scales associated with satellite missions. Two recent NRC studies in this regard, *Restructuring Federal Climate Research to Meet the Challenges of Climate Change* (2009)[28] and *America's Climate Choices: Advancing the Science of Climate Change* (2010),[29] have both highlighted this key deficiency. For example, the transition of precision ocean altimetry took 20 years, moving from a joint U.S./France research capability to a joint U.S./Europe operational capability. At each step of this process, there was a risk of failure, potentially creating a gap in a critical observational record. Future U.S. participation is, at present, uncertain and in jeopardy.

The 2007 decadal survey recommended that "the Office of Science and Technology Policy, in collaboration with the relevant agencies and in consultation with the science community, should develop and implement a plan for achieving and sustaining global Earth observations. This plan should recognize the complexity of differing agency roles, responsibilities, and capabilities as well as the lessons from the implementation of the Landsat, EOS, and NPOESS programs."[30] This same recommendation was echoed in a 2008 follow-on report, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft,* which further explored in its Chapter 4 the elements needed for a long-term climate strategy.[31] A more complete plan for achieving and sustaining global Earth observations, as called for in the 2007 decadal survey and the 2008 NRC follow-on report, remains to be presented or funded. However, the NASA Climate-Centric

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27, 2010, available at http://www.gao.gov/new.items/d10456.pdf) draws heavily from the National Research Council studies cited above, especially the 2007 decadal survey. Other relevant GAO reports include *Polar-Orbiting Environmental Satellites: Agencies Must Act Quickly to Address Risks That Jeopardize the Continuity of Weather and Climate Data* (GAO-10-558, May 27, 2010) and *Environmental Satellites: Polar-orbiting Satellite Acquisition Faces Delays; Decisions Needed on Whether and How to Ensure Climate Data Continuity* (GAO-08-899T, June 19, 2008), all published by the Government Accountability Office, Washington, D.C.

[27]As discussed in the National Research Council report *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft,* 2008.

> Much of climate science depends on long-term, sustained measurement records. Yet, as noted in many previous NRC and agency reports, the nation lacks a clear policy to address these known national and international needs. A coherent, integrated, and viable long-term climate observation strategy should explicitly seek to balance the myriad science and applications objectives basic to serving the variety of climate data stakeholders. The program should, for example, consider the appropriate balance between (1) new sensors for technological innovation, (2) new observations for emerging science needs, (3) long-term sustainable science-grade environmental observations, and (4) measurements that improve support for decision making to enable more effective climate mitigation and adaptation regulations. The various agencies have differing levels of expertise associated with each of these programmatic elements, and a long-term strategy should seek to capitalize on inherent organizational strengths where appropriate.

[28]National Research Council, *Restructuring Federal Climate Research to Meet the Challenges of Climate Change,* The National Academies Press, Washington, D.C., 2009.

[29]National Research Council, *America's Climate Choices: Advancing the Science of Climate Change,* The National Academies Press, Washington, D.C., 2010.

[30]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 14.

[31]National Research Council, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft,* 2008.

Architecture plan released in 2010[32] includes a set of Climate Continuity missions, tacitly recognizing for the first time NASA's role in sustained observations.

> **Finding:** The 2007 decadal survey's recommendation that the Office of Science and Technology Policy develop an interagency framework for a sustained global Earth observing system has not been implemented. The committee concluded that the lack of such an implementable and funded strategy has become a key, but not the sole, impediment to sustaining Earth science and applications from space.

The committee does not propose a specific leadership and management framework, but rather notes that such a national strategy should:

- Lead to more effective and resilient interagency collaborations and build a predictable and persistent partnership between the research and operational satellite agencies;
- Establish priorities that allow the strategy to be implemented, consistent with national and agency-specific priorities, given cost and technical constraints;
- Evaluate the present informal relationship between NASA and NOAA as well as the emerging partnership between NASA and the USGS (and NASA/NOAA and the Environmental Protection Agency). This evaluation would be done in the context of the numerous NRC studies on research and operational partnerships to support the development of a climate observing system that would ensure the continuity of climate data records;
- Examine the design, development, and testing of new spacecraft and instruments and the manner by which they are inserted into operational or sustained monitoring;
- Develop and sustain international partners as appropriate and give priority to those partnerships (see the section "International Partnerships" in Chapter 4);
- Set forth a sustainable space-based architecture that takes into account formation flying, constellation approaches, free-flyers and small satellites, sensor overlap, calibration, and low Earth orbit, geostationary, and polar orbits (see the section "Alternative Platforms and Flight Formations" in Chapter 4);
- Engage the broad Earth system science research and applications community at key decision points such as contingency planning.

NOAA MISSIONS

Although the focus of this report is on NASA, the 2007 decadal survey recognized that the research programs of NASA and the operational programs of NOAA are necessary components of a U.S. Earth observation program from space that serves both science and society.[33] In particular, NOAA's current and planned polar and geostationary programs were an integral part of the baseline capabilities assumed by the survey committee members as they developed their integrated strategy, and 2 of the survey's recommended 17 missions were directed for implementation by NOAA.[34] NOAA and NASA work closely together

[32]NASA, *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space,* June 2010; available at http://science.nasa.gov/media/medialibrary/2010/07/01/Climate_Architecture_Final.pdf.

[33]The statement of task for the decadal survey stated, "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" (National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 381).

[34]One mission, CLARREO, included a component to be implemented by NOAA.

on many NOAA missions, and the success and failures of NOAA often impact the NASA programs, and vice versa. Hence the present committee found it appropriate to review progress and issues at NOAA with respect to the decadal survey recommendations. A recommendation-by-recommendation discussion (using the recommendations from the survey) is provided in Appendix D; a summary is provided in Table 3.1. Based on the review provided in Appendix D, the committee found as follows:

> **Finding:** NOAA's capability to implement the assumed baseline and the recommended program of the 2007 decadal survey has been greatly diminished by budget shortfalls; cost overruns and delays, especially those associated with the NPOESS program prior to its restructuring in 2010 to become the Joint Polar Satellite System (JPSS); and by sensor descopes and sensor eliminations on both NPOESS and the Geostationary Orbit Environmental Satellite-R Series (GOES-R).[35]

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[35]Even before the latest round of budget-driven delays and descopes, NOAA polar and geostationary programs had experienced severe budget challenges with particular consequences for research and operations deemed outside required "core" capabilities. See National Research Council, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring,* The National Academies Press, Washington, D.C., 2008. The Government Accountability Office (GAO) has published a number of reports detailing the origins of the cost overruns and assessing program management. See, for example, GAO, *Polar-orbiting Environmental Satellites: Agencies Must Act Quickly to Address Risks That Jeopardize the Continuity of Weather and Climate Data,* GAO-10-558 (Washington, D.C., May 10, 2010) and *Polar-orbiting Environmental Satellites: With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making,* GAO-09-564 (Washington, D.C., June 17, 2009).

TABLE 3.1 Summary of Decadal Survey Related NOAA Developments

Capability	Current Status
NPOESS	Canceled in 2010 and split into separate NOAA (JPSS) and Air Force (DWSS) programs. JPSS is experiencing delays as a result of significant shortfalls in the requested funding for FY2011. The joint NASA/NOAA NPP mission was launched successfully on October 28, 2011.
Restore descoped sensors	No NPOESS climate sensors flown.
Aerosol Polarimetry Sensor (APS)	Failed to reach orbit due to the Glory launch vehicle failure.
Total Solar Irradiance Sensor (TSIS)	TIM instrument on Glory failed to reach orbit due to the Glory launch vehicle failure. TSIS (TIM + SIM) is currently NOAA's highest priority for flight of the canceled NPOESS climate sensors. Several options, including a free-flyer mission for a TIM, are under consideration.
Ozone Monitoring and Profiling Suite (OMPS) - Limb	On NPP, but not on JPSS-1. Planned to be included on JPSS-2 launching no earlier than 2019.
Earth Radiation Budget Sensor (ERBS)	Clouds and Earth's Radiant Energy System (CERES) instrument on NPP and JPSS-1 no earlier than 2017; no current plans to fly an ERBS as a follow-on to CERES.
Altimeter (ALT)	Canceled on NPOESS/JPSS. Altimetry measurements will be provided by the Jason series of spacecraft; however, in part due to budgetary shortfalls at NOAA, the next in the series, Jason-3, will launch no earlier than April 2014, 6.5 years after the launch of Jason-2. Additional delays are likely due to both budgetary problems and the negative impact of two recent Taurus XL launch failures.
Ocean Vector Winds (aka XOVWM)	In an effort to establish an operational ocean surface vector wind satellite capability, NOAA NESDIS had been exploring the possibility of flying a U.S. scatterometer (DFS—dual frequency scatterometer) on board the Japan Aerospace Exploration Agency's (JAXA's) Global Change Observation Mission (GCOM) satellite series. NOAA has now announced that it does not have the ability to fund this effort and has requested that NASA assume responsibility for the provision of ocean surface vector winds data.
GOES-R/Hyperspectral Environmental Suite (HES)	Advanced atmospheric sounder requirement deleted from GOES-R program. As a result, U.S. geosynchronous sounding capability will end after GOES-N/O/P.
COSMIC-2 (aka GPSRO)	A plan is in place with the U.S. Air Force for a 12-satellite constellation; however, the President's budget for NOAA for FY2011 and FY2012, which included funds for COSMIC-2, was zeroed by Congress. As this report went to press, the Air Force announced that it would fund at least six of the payloads for COSMIC-2 and provide a launch.
Deep Space Climate Observatory (DSCOVR)	The Earth-viewing instruments of DSCOVR were not identified as a decadal survey priority; however, the survey noted the important use of the DSCOVR spacecraft bus as a platform for space weather instruments at L1. NOAA did not receive funding for DSCOVR in FY2011; however, the FY2012 enacted budget provided $29.8 million. The U.S. Air Force will pay for the launch of DSCOVR, which is now planned for 2014.

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Opportunities to Improve Alignment with Decadal Survey Priorities

The inefficiencies associated with budget instability and continuing shifts in administration and congressional priorities warrant a more dynamic and robust approach to making progress on the 2007 Earth science and applications from space decadal survey vision and recommendations.[1] NASA's Earth Observing System (EOS), conceived in the 1980s and implemented in the 1990s,[2] benefited from structures that existed within the NASA program that enabled senior principal investigators and engineers associated with missions and instruments to meet frequently and provide day-to-day advice to NASA managers about, for example, changes in scope and plans, new technology options, and new mission architectures. The EOS Payload Panel and Interdisciplinary Science Principal Investigators were the most visible of such groups, and their experience was built on an overall philosophy of engaging the science community and mission and instrument engineers in a coordinated way, and then using their input as a major contribution to difficult operational decisions about missions and instruments. These working groups were outside the formal broad advisory structure of the NASA Advisory Committees and the National Academies but had the benefit that they were intimately familiar with the details and overall goals of the NASA program. This committee does not see that such management structures currently exist to provide an ongoing source of broad Earth science community involvement. As a result, difficult decisions are made largely without coordinated community input, because infrequent meetings with existing high-level oversight committees cannot delve into issues at the needed level of detail.

[1]The 2007 decadal survey recommended that NASA "[i]mplement a system-wide independent review process that permits decisions regarding technical capabilities, cost, and schedule to be made in the context of the overarching science objectives. Programmatic decisions on potential delays or reductions in the capabilities of a particular mission would be evaluated in light of the overall mission set and integrated requirements" (p. 11). This statement is reiterated here in the form of a recommendation. See National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (The National Academies Press, Washington, D.C., 2007), which included guidance in Box 3.4 for the case of budget shortfalls.

[2]See CIESIN, "EOS Program Chronology," available at http://www.ciesin.org/docs/005-089/005-089art2.html, reproduced from NASA, *Earth Observing System (EOS) Reference Handbook,* G. Asrar and D.J. Dokken, eds., NASA Earth Science Support Office, Document Resource Facility, Washington, D.C., 1993.

An overarching cross-mission science and applications coordination effort would help ensure that programmatic decisions on potential delays or augmentations/reductions in the capabilities of a particular mission would be evaluated in light of the overall mission set and integrated requirements rather than as "one off" decisions.[3] The science and applications coordination effort should include appropriate interaction with the already-established system engineering working group[4] and mission system engineering teams to stay apprised of cross-mission areas of mutual interest[5] and should be conducted in an ongoing manner as science requirements and mission designs and costs evolve—with the participation of other agencies and international partners/stakeholders when appropriate.

ESTABLISHING AND MANAGING MISSION COSTS

As discussed in Chapter 3, the 2007 decadal survey report put forth mission concept descriptions and notional costs that were intended mainly to set targets for each mission that are consistent with an overall program that is affordable while denoting the relative cost of one mission with respect to another, which factored into mission priority and phasing.[6] After release of the survey, teams were formed by NASA to further develop each of the recommended mission concepts. Based on discussions with the director of the Earth Science Division (ESD) and individual mission team members, the committee learned that teams operated primarily in a "requirements-gathering" mode, unconstrained by even notional cost targets.[7] Unfortunately, this approach created an atmosphere in which science requirements and scope tended to grow, as did cost estimates.[8] Furthermore, there was apparently insufficient consideration given to the effect of individual mission cost growth on the entire queue of recommended missions.

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[3]This cross-mission science and applications coordination effort could, for example, encourage studies and trades across missions where synergies anticipated in the survey report might not be readily realized in the mission concepts as presented, or within available resources. Indeed, the need for further optimization was recognized by the survey authors, who stated, "The selected missions reflect the panels' prioritization of scientific observations but are not the result of an exhaustive examination of the trade-offs across the entire range of potential missions. Clearly, more detailed cost estimates are needed that examine the full range of mission trade-offs.…" (National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, 2007, p. 43.)

[4]The Earth Systematic Missions Program Office has established a systems engineering working group with representatives from each center.

[5]Science stakeholder participation in the A-Train Constellation Mission Operations Working Group is an example of such effective interaction.

[6]The decadal survey cost estimation process and purpose are described further in Box 2.3 in the 2007 report: "Nevertheless, the estimates provided in this study set targets for each mission that are consistent with an overall program that is also affordable. The panels recognize that the missions afforded under the estimated costs will be ones that respond to the main scientific requirements articulated by the panels in Chapters 5 through 11, but not necessarily all of the desired requirements. The selected missions reflect the panels' prioritization of scientific observations but are not the result of an exhaustive examination of the trade-offs across the entire range of potential missions. Clearly, more detailed cost estimates are needed that examine the full range of mission trade-offs. Where possible within budget constraints, augmentation of the specified set of science observations with additional desired observables should be considered; however, NASA and the scientific community must avoid 'requirements creep' and the consequent damaging cost growth" (National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007, p. 43).

[7]The discussion between the ESD director and the committee took place on April 28, 2011, during the committee's first meeting in Washington, D.C. Discussions with mission team members took place during the committee's first and second meetings, the latter of which was held on July 6-8, 2011.

[8]The bulk of early formulation funding went directly to the science community to support "requirements gathering." Without pushback from engineering or cost experts, requirements can accumulate with minimal challenges or controversy. The sense is that the science is paramount and, as long as the mission is far in the future, anything is considered possible. However, this approach nurtures the development and maintenance of sometimes inappropriately high expectations and can result in untenably high costs and high cost risk.

The success of all missions is ultimately critically dependent on an end-to-end partnership between the science team and the engineering team to ensure that an iterative process emerges that continuously balances all of a mission's constraints, both technical and programmatic. Instead of a process that starts with gathering science requirements and then determining the resulting cost of a derived mission, those with science, engineering, systems engineering, and cost expertise should *all* be involved from the beginning. By understanding the source of various requirements, their relative priorities, and the consequences of designing to satisfy the requirements, engineers are better able to push back if incremental science requirements will drive up a mission design's cost or risk, identifying the "knees in the curves," and interacting with the science stakeholder community in a productive and iterative fashion toward development of a truly optimized design.[9] By fully sensitizing all involved to the factors associated with implementing and costing a mission, this interaction can help minimize the "sticker shock" associated with individual missions when they are handed off from the broader science community to the mission implementers.

Early establishment of cost and schedule constraints would allow an iterative process to emerge that could continuously balance all of the mission constraints within a known and achievable funding envelope, leading to a more robust yet affordable implementation. This way, the team can be focused on maximizing science return on investment rather than attempting to craft a "perfect" yet unaffordable mission. The committee found that process transparency is essential to ensure that the implementation of the decadal survey is regarded as a community-driven effort and not one driven by local or vested interests, and thus offers the following recommendation:

Recommendation:

- **NASA's Earth Science Division (ESD) should implement its missions via a cost-constrained approach, requiring that cost partially or fully constrain the scope of each mission such that realistic science and applications objectives can be accomplished within a reasonable and achievable future budget scenario.**

Further, recognizing that survey-derived cost estimates are by necessity very approximate and that subsequent, more detailed analyses may determine that all of the desired science objectives of a particular mission cannot be achieved at the estimated cost,

- **NASA's ESD should interpret the 2007 decadal survey's estimates of mission costs as an expression of the relative level of investment that the survey's authoring committee believed appropriate to advance the intended science and should apportion funds accordingly, even if all desired science objectives for the mission might not be achieved.**

To coordinate decisions regarding mission technical capabilities, cost, and schedule in the context of overarching Earth system science and applications objectives, the committee also recommends that

- **NASA's ESD should establish a cross-mission Earth system science and engineering team to advise NASA on execution of the broad suite of decadal survey missions within the interdisciplinary context advocated by the decadal survey. The advisory team would assist NASA in coordinating**

[9] End-to-end system simulations performed prior to Preliminary Design Review can help to quantitatively identify the cost/benefit ratios for the baseline design, as well as a range of alternatives.

decisions regarding mission technical capabilities, cost, and schedule in the context of overarching Earth system science and applications objectives.[10,11]

INTERNATIONAL PARTNERSHIPS

The roots of international partnerships and joint missions to observe Earth from space come from the International Geophysical Year in the late 1950s. Throughout the 1960s and 1970s and peaking with the Global Weather Experiment (GWE) and the World Weather Watch in 1979, both bilateral and multinational space missions for weather, climate, and ocean observations became the norm. These international activities are fostered by the International Council of Scientific Unions (ICSU), the World Meteorological Organization of the United Nations, and others. NASA and other national space agencies, as well as the National Oceanic and Atmospheric Administration (NOAA) and other national weather/climate agencies, have decades of experience with joint space missions as well as hosting another nation's instruments on their spacecraft.

On June 28, 2010, President Obama issued the new National Space Policy. One of the policy's goals is expanded "international cooperation on mutually beneficial space activities to: broaden and extend the benefits of space; further the peaceful use of space; and enhance collection and partnership in sharing of space-derived information."[12] The policy further calls on departments and agencies to "identify potential areas for international cooperation that may include … Earth science and observation; environmental monitoring; … geospatial information products and services … disaster mitigation and relief …."; and other areas, as well. It further looked to "promote appropriate cost- and risk-sharing among participating nations in international partnerships; and augment U.S. capabilities by leveraging existing and planned space capabilities of allies and space partners." Clearly, this policy seeks to mitigate U.S. budget shortfalls through a non-zero-sum game, enabling increased accomplishment through international cooperation. International joint missions, hosted instruments, shared data, and coordinated satellite constellations are all becoming new realities. As such international cooperation spreads into all areas of Earth science it becomes natural and essential to include significant specific international partnerships in the planning and implementation of any Earth science and applications from space decadal survey. Several examples of international collaborations are provided below to illustrate the variety of scopes and scales such collaborations can involve.

- The successful June 10, 2011, launch and orbital insertion of the Aquarius/Satélite de Aplicaciones Científicas (SAC)-D mission to globally measure sea-surface salinity features an international partnership between NASA and Argentina's space agency, Comision Nacional de Actividades Espaciales (CONAE).[13] The 3-year mission (the fourth of this collaboration) includes a NASA instrument, an Argentine spacecraft, and a launch from Vandenberg Air Force Base on a Delta II launch vehicle.

[10]The team, similar to the Payload Advisory Panel established by NASA to assist in implementation of its Earth Observing System (EOS), would draw its membership from the scientists and engineers involved in the definition and execution of survey missions as well as the nation's scientific and engineering talent more broadly. (The Payload Advisory Panel was composed of the EOS Interdisciplinary Science Investigation principal investigators and was formally charged with examining and recommending EOS payloads to NASA based on the science requirements and priorities established by the Earth science community at large.) See NASA, *Earth Observing System (EOS) Reference Handbook,* G. Asrar and D.J. Dokken, eds., NASA Earth Science Support Office, Document Resource Facility, Washington, D.C., 1993.

[11]The committee believes that NASA is best positioned to determine whether this advisory panel should be constituted as a Federal Advisory Committee Act-compliant advisory body.

[12]See http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf.

[13]See http://aquarius.nasa.gov/overview.html.

- FORMOSAT-3/COSMIC, the joint Taiwan/U.S. science mission for weather, climate, space weather, and geodetic research, was launched on April 14, 2006. The mission, which includes six identical microsatellites launched together on a Minotaur vehicle, currently provides thousands of daily radio occultation profiles that yield accurate and precise information on temperature, water vapor, and electron density.[14] COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) has contributed significantly to ionospheric, stratospheric, and tropospheric sciences and to applications for space weather, weather prediction, and climate science.[15] The FORMOSAT-7/COSMIC-2 planned joint mission (Appendix D), however, is at risk because of a lack of NOAA funding commitment to match Taiwan's $160 million commitment and a similar level of support from the U.S. Air Force.
- The joint Japanese-U.S. Global Precipitation Mission (GPM)—a joint NASA/JAXA mission—is to be launched in 2013 (Figure 4.1). For this mission Japan provides the Dual-frequency Precipitation Radar (DPR) instrument and HII-A launch vehicle, and the United States provides the GPM Microwave Imager (GMI) instrument, the spacecraft, and other system components. Major international partners also include France and Canada.
- NASA and the German Aerospace Center (DLR) jointly developed the twin-satellite Gravity Recovery and Climate Experiment (GRACE) mission (launched in March 2002) and are continuing to cooperate throughout its operational phase. NASA and DLR plan to fly a GRACE follow-on continuity mission to extend the measurement of changes in microgravity due to variability (e.g., depletion, recovery) in continental aquifers, polar ice mass changes, and so on.[16]
- The Initial Joint Polar System Agreement,[17] made between NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) in 1998, created the framework for two polar-orbiting satellite systems and their respective ground systems. This agreement—whereby EUMETSAT flies the mid-morning weather and environmental platform, and NOAA flies in the early afternoon—continues to work exceedingly well to provide meteorological and environmental forecasting and global climate monitoring services worldwide.[18] It is sustained through ongoing working groups, cross-participation in satellite meteorology, oceanography, and climate conferences, and the dedication of a small number of individuals in the United States and Europe. NOAA/NESDIS and EUMETSAT are working to establish the renewed Joint Polar System by 2018.[19]

Recent developments in bilateral and multilateral sharing of Earth remote sensing data have been encouraging. In a continuation of its policy of open access to science data, the United States has made Landsat data widely available, and the number of data downloads, users, and applications has increased from thousands to millions.[20] Working through the Global Climate Observing System (GCOS) and the Committee on Earth Observations Satellites (CEOS), NASA and NOAA coordinate activities to ensure international coordination of long-term mission planning activities and progress on issues of mutual interest. Several agreements between NASA and NOAA with international groups will bring Japanese Global Change

[14]See http://www.cosmic.ucar.edu/index.html.

[15]See http://www.atmos-meas-tech.net/4/1077/2011/amt-4-1077-2011.html.

[16]See http://www.csr.utexas.edu/grace/. The GRACE follow-on mission is a climate continuity mission called for in NASA, *Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space,* June 2010, available at http://science.nasa.gov/media/medialibrary/2010/07/01/Climate_Architecture_Final.pdf.

[17]See http://www.eumetsat.int/Home/Main/AboutEUMETSAT/InternationalRelations/KeyPartners/ SP_1225965119191.

[18]See http://projects.osd.noaa.gov/IJPS/.

[19]See http://www.eumetsat.int/Home/Main/AboutEUMETSAT/InternationalRelations/KeyPartners/ SP_1225965119191.

[20]U.S. Geological Survey, "Free Landsat Scenes Go Public by the Million," USGS Newsroom, August 20, 2009, available at http://www.usgs.gov/newsroom/article.asp?ID=2293&from=rss_home.

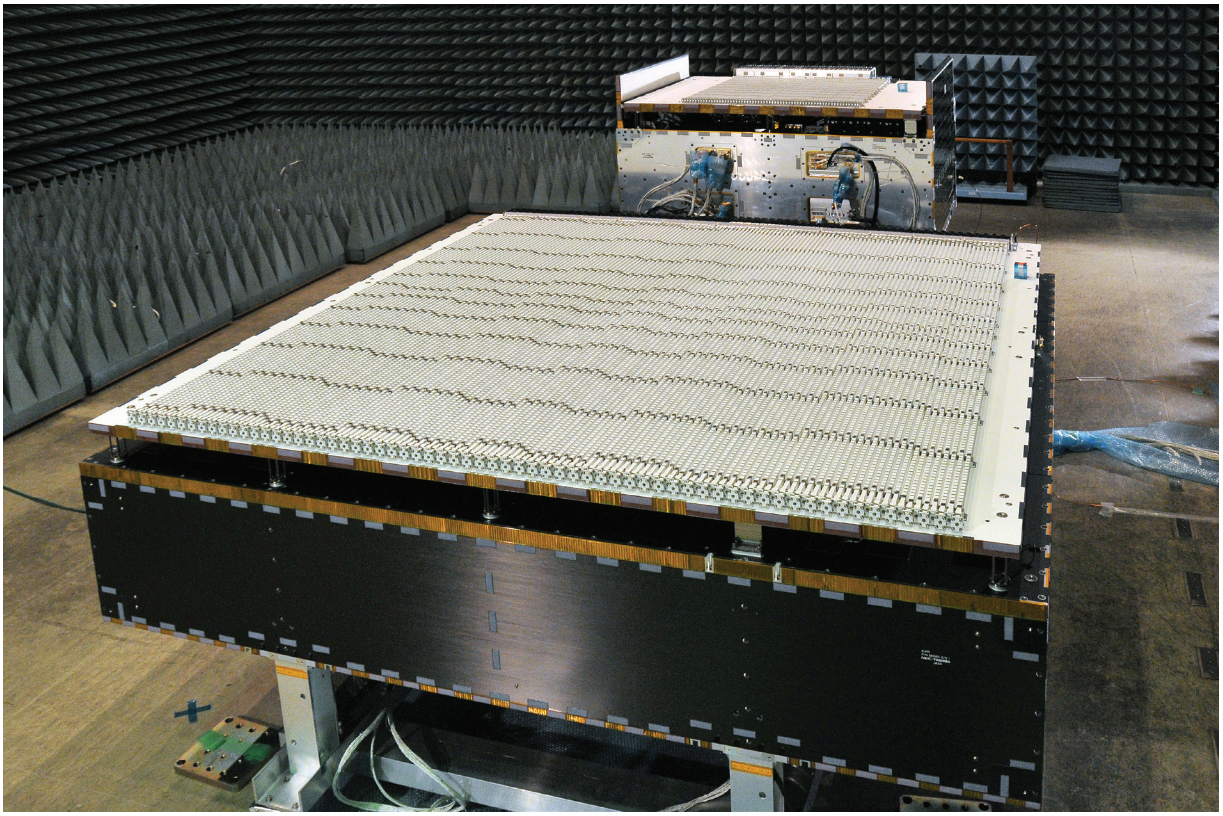

FIGURE 4.1 The Dual Frequency Precipitation Radar instrument that will fly on the Global Precipitation Measurement mission. SOURCE: Copyright © Japan Aerospace Exploration Agency.

Observation Mission-Climate (GCOM-C) and GCOM-W (water) data to the United States as well as the EUMETSAT MetOp data. In addition, the 2007 survey's Surface Water and Ocean Topography (SWOT) mission is being considered as a multidisciplinary cooperative international effort that builds on a long-lived and successful U.S. and French partnership. The SWOT satellite mission will expand on previous altimetry flights (e.g., TOPEX/Poseidon) through wide-swath altimetry technology to achieve complete coverage of the world's oceans and freshwater bodies with repeated high-resolution elevation measurements.[21]

International collaborations are well aligned with the first recommendation of the 2007 decadal survey that "the U.S. government, working in concert with … international partners, should renew its investment in Earth-observing systems and restore its leadership in Earth science and applications" (p. 2). As noted in the 2011 National Research Council (NRC) report *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*:[22]

[21]See http://swot.jpl.nasa.gov/mission/.

[22]National Research Council, *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions,* The National Academies Press, Washington, D.C., 2011.

> A prerequisite for a successful international collaboration is that all parties believe the collaboration is of mutual benefit.… agreements should not be entered into lightly and should be undertaken only with a full assessment of the inherent complexities and risks. (p. 2)

Current opportunities for new partnerships might be found, among others, with the European EarthCARE joint European-Japanese mission that observes the climate-related interactions among cloud, radiative, and aerosol processes; the Atmospheric Laser Doppler-Lidar Instrument (Aladin) on the Atmospheric Dynamics Mission-Aeolus (ADM-Aeolus), with DLR for a Tandem-L InSAR mission.

Finding: NASA has made considerable efforts to secure international partnerships to meet its science goals and operational requirements.

ALTERNATIVE PLATFORMS AND FLIGHT FORMATIONS

In addition to traditional launches on dedicated, large spacecraft, a number of promising alternative platforms and observing strategies are emerging and being proven. These include flights on piloted[23] and/or unpiloted aircraft, hosted payloads on commercial satellites,[24] small satellites, the International Space Station, and the flight of multiple sensors in formations rather on a single bus.[25] These alternative mission concepts can offer considerable implementation flexibility.

Suborbital Campaigns

Instrument accommodation on balloons, piloted aircraft, and unpiloted aerial vehicles (UAVs) provides a rapid and cost-effective means for proof-of-concept studies, technology maturation, or actual research/operational use. Their utility was recognized by NASA in the first Earth Venture (EV-1) announcement of opportunity, from which a diverse portfolio of five science investigations was selected.[26]

Hosted Payloads

Also referred to as secondary payloads, hosted payloads take advantage of available capacity on commercial (e.g., communications) satellites to accommodate communications or science instruments. The Department of Defense (DOD) has been successful in using hosted payload concepts to lower program costs. NASA's recently released draft solicitation for the first Earth Venture-Instruments (EV-I) calls for principal investigators to propose instruments for hosting on platforms of opportunity, which can include commercial satellites, opening the door to leveraging hosted payload capacity to advance NASA Earth science.[27]

Small Satellites

Small satellites, notionally those with spacecraft masses less than 500 kg,[28] can enable rapid development strategies (less than 36 months) that lower development costs. A 2000 NRC report, *The Role of Small Satellites in NASA and NOAA Earth Observation Programs,* provides an analysis of the role of small satel-

[23] See http://www.nasa.gov/mission_pages/icebridge/index.html.
[24] See http://hostedpayloadalliance.org/.
[25] See http://www.nasa.gov/mission_pages/a-train/a-train.html.
[26] See http://www.nasa.gov/home/hqnews/2010/may/Hq_10-127_Venture_Program.html.
[27] See http://essp.larc.nasa.gov/EV-I/.
[28] The ~450 kg OCO (and OCO-2) and the 70 kg COSMIC satellites are examples of small satellites.

lites in Earth observation, particularly in the context of complementing (not replacing) larger missions.[29] Especially when configured with single sensors, small satellite missions can add significantly to architectural and programmatic flexibility. An emphasis on smaller platforms also potentially reduces cost through the use of smaller and cheaper launch vehicles, including opportunities for launching multiple payloads on a single launch vehicle, and "piggyback" launches, using excess capacity on larger launch vehicles.

International Space Station

In 2007, the Hyperspectral Imager for the Coastal Ocean (HICO) was manifested for the Japanese Experiment Module-Exposed Facility (JEM-EF) on the International Space Station (ISS), and installed on orbit on September 24, 2009. HICO was sponsored by the Office of Naval Research (ONR) to "develop and operate the first Maritime Hyperspectral Imaging from space."[30] HICO was integrated and flown under the direction of DOD's Space Test Program. One of the HICO mission requirements was to "demonstrate new and innovative ways to develop and build the imaging payload (reduce cost, reduce schedule)."[31] The sensor was delivered 16 months after project start and was installed within a total time of 3 years of its proposal. HICO has since met its demonstration requirement. HICO's implementation demonstrated that the ISS is a viable platform for demonstrations of Earth observing technologies and Earth observations.[32] (See Figure 4.2.) Another instrument scheduled for manifestation on the ISS is NASA's Stratospheric Aerosol and Gas Experiment III-ISS (SAGE III-ISS) to measure atmospheric ozone, water vapor, and aerosols. SAGE III is scheduled for launch in 2014 on a SpaceX rocket from NASA Kennedy Space Center.[33]

Flight Formations

Formation flying can deliver multiple benefits, not the least of which is the ability to flexibly combine (and maintain over time) multiple, synergistic, and multisensor measurement types.[34] Advances in both station-keeping ability and coordination protocols now make it possible to achieve formation flight with a diverse set of spacecraft, whether launched simultaneously or years apart, including the large EOS observatories, small satellites, and co-manifested satellites. Constellations may remain in place beyond the lifetime of individual satellites if appropriate planning and funding remain in place. The Afternoon Constellation (A-Train) continues to exemplify the best of international scientific cooperation and coordination[35] and can provide valuable experience, best practices, and lessons learned for future constellation efforts (e.g., potential establishment of a constellation based on the Joint Polar Satellite System, JPSS). Coordinated formation flight efficiencies can include the synergies of complementary measurements, where the assigned degree

[29] National Research Council, *The Role of Small Satellites in NASA and NOAA Earth Observation Programs*, National Academy Press, Washington, D.C., 2000.

[30] M.R. Corson (Naval Research Laboratory) and C.O. Davis, (Oregon State University), "HICO Science Mission Overview," available at http://hico.coas.oregonstate.edu/publications/Davis_HICO_for%20IGARSS.pdf, p. 22.

[31] Corson and Davis, "HICO Science Mission Overview," p. 7.

[32] See http://www.ioccg.org/sensors/Davis_HICO_IOCCG-15.pdf.

[33] See http://www.nasa.gov/topics/earth/features/sage3.html.

[34] Formation flight can provide a much clearer way of quantifying errors in parameter estimation and identifying major biases/flaws in past data derived from single sensors. For example, the combined cloud information from CALIPSO and CloudSat has exposed significant biases in interpretation of ISCCP (International Satellite Cloud Climatology Project) global cloudiness, the combination of CALIPSO and CloudSat has led to a new and more accurate way of retrieving aerosol optical depth, and CALIPSO has yielded powerful new information about polar stratospheric clouds, and so on.

[35] See http://atrain.nasa.gov/, http://www.nasa.gov/mission_pages/a-train/a-train.html, and http://eospso.gsfc.nasa.gov/eos_observ/pdf/Jan-Feb_2011_color_508.pdf.

FIGURE 4.2 HICO image of the Straits of Gibraltar, December 5, 2009. SOURCE: Naval Research Laboratory; available at http://hico.coas.oregonstate.edu/gallery/gallery-scenes.shtml.

of simultaneity is based on position within the train; train permanence (with its composition changing over time);[36] a ready mechanism for international cooperation; technology insertion, with research and operational technologies operating side by side; the avoidance of engineering complexities and management difficulties associated with integration on a common bus; and a more agile and cost-effective replacement of individual sensors. Also important is the role of formation flight in enabling Earth system science by moving away from a single parameter and sensor-centric approach toward a systems approach that ties observations together to study processes important to understanding Earth-system feedbacks.[37]

Finding: Alternative platforms and flight formations offer programmatic flexibility. In some cases, they may be employed to lower the cost of meeting science objectives and/or maturing remote sensing and in situ observing technologies.

[36]S.W. Boland, M.D. Garcia, M. Vincent, S. Hu, P.J. Guske, and D. Crisp, "Ground Track Selection for the Orbiting Carbon Observatory-2 Mission," American Geophysical Union Fall Meeting 2011, abstract #A33C-0242, American Geophysical Union, 2011.

[37]For example, the combination of water vapor and temperature from AIRS, together with proper cloud screening tested with other data, has provided insight on the strength of water vapor feedback; the combination of MODIS, AMSR-E, and CloudSat has revealed new insights on rain-forming processes, thus exposing major biases in climate model parameterizations; and the combination of AIRS, CloudSat, and CERES is being used to understand the sources of seasonal loss of sea ice in the Arctic.

5

Looking Ahead: Beyond 2020

In this chapter, the committee provides a summary of observations and lessons learned during its assessment of the NASA Earth science program and NASA's progress in implementation of the 2007 Earth science and applications from space decadal survey.[1] The committee provides these observations in the belief that they will prove useful in optimizing the science value of the Earth science program going forward. It also believes that these observations will be useful to future advisory committees that may be charged with developing the next major iteration of the decadal survey. However, the committee also recognizes that advances in Earth science and in technology, and/or changes in U.S. government policy or funding related to Earth science that cannot be foreseen, may preclude or negate consideration of some of its guidance.

MAINTAINING A LONG-TERM VISION

Although changes or advances in the field might necessitate alterations to the Earth science program over time, *the committee believes that any future study aimed at designing a new set of missions for the Earth science program should retain a long-term focus on the program priorities that underlie the current mission queue, even as it recommends new avenues for investment based on scientific and technological progress over the time period established by such a study (e.g., a decade).* Future mission queues drawing from those provided in the decadal survey would likely best serve both the science community and applications end users by leveraging progress already made on missions in implementation or formulation and by continuing the legacy of what the first decadal survey of Earth science and applications from space, the 2007 decadal survey, set out to accomplish. Retaining a fixed, predictable mission queue is essential to preventing devolution into mission- or discipline-specific advocacy groups that can seriously damage the community-based priorities established by the survey and undermine the community consensus critical to any major programmatic review. With a fixed and predictable queue, communities with missions ap-

[1]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

pearing later in the queue have some assurance that the mission will indeed be implemented and remain an integral part of Earth system science. Retention of and investment in such long-term priorities are thus crucial to enabling a balanced program and reaffirming NASA's commitment to the entire suite of missions. To maintain the survey's long-term vision for a balanced Earth system science and applications program, this fixed and predictable queue would be complemented by a steady stream of opportunities to facilitate the demonstration of innovative ideas and higher-risk technologies to provide a mechanism to support new discoveries and add an element of flexibility to the program.

MISSION RECOMMENDATIONS

The science priorities identified by the 2007 decadal survey have provided the foundation for advancing Earth system science with the recommended set of missions. In its assessment of NASA's implementation of the survey, the committee discussed at length whether specific mission recommendations were a necessary part of science priority setting, and presenters to the committee over the course of the study did not always favor one approach over the other. Finding balance between prioritizing science objectives and constraining how those objectives are accomplished will no doubt be one of the major tasks for any future study aimed at creating a new mission queue and set of scientific objectives for NASA's Earth science program. *However, the committee concluded that establishing at least notional mission concepts that can accomplish the prioritized objectives is essential to ensuring that the priorities are indeed reasonable and achievable.* Similarly, development of mission recommendations allows for a sense of scope and scale to be conveyed that is lacking from a simple listing of target areas for investment. The committee thought that establishing science priorities devoid of implementation recommendations could easily be misconstrued as endorsements for one discipline over another.

COST ESTIMATION AND BUDGETARY MANAGEMENT

In the course of this midterm assessment of the 2007 decadal survey's implementation, it became apparent to the committee that large cost growth in missions early in the queue presents a real danger to programmatic balance. It also tends to encourage commensurate growth in later missions, effectively stretching program implementation and pushing later missions inexorably toward future dates, thus discouraging entire segments of the Earth science community and threatening the Earth system science goals set forth by the survey.

However, future community prioritization exercises should avoid pursuing the path of ever-more-detailed cost estimates at the expense of attention to scientific priority setting—the latter being the primary goal of any such review. Even in a cost-constrained environment, some mission cost growth is likely, if not inevitable. The committee does not discourage rigorous cost estimation at the appropriate time during formulation, a practice that serves an important purpose—but equally important is setting up clear budgetary decision rules that will help decision makers adjust to a changing fiscal environment and maintain the overall goals laid out in the vision put forth in any suggested future program.[2] *To supplement such budgetary decision rules, consideration should be given to the use of mission cost caps that would help prevent*

[2]Consideration should be given to establishing relative investment levels for recommended missions rather than leaving the cost of recommended missions unconstrained. Individual missions, then, would not claim enduring priority over other missions regardless of ultimate implementation cost, thus facilitating maintenance of programmatic balance across Earth system science. NASA would set an appropriate cost cap once more detailed implementation studies, guided by the recommended investment level, have been completed. The 2007 decadal survey attempted to convey a sense of scale through its rough cost estimates, but it stopped short of establishing or recommending a cost cap approach.

science-requirements creep from being the primary driver in mission design and development, a situation that has led to near-catastrophic cost estimate growth with some of the current decadal survey missions.[3]

Although the 2007 decadal survey presented a number of strategies and rules to help alleviate potential budgetary pressures placed on the Earth science program and implementation of the survey missions (Appendix B), more proscriptive decision rules and /or an explicit recommendation to implement missions via a cost-constrained approach might have been more useful in giving program managers a clearer idea of how to proceed to accomplish science objectives and maintain a healthy and balanced portfolio in the face of program adversity. The committee also recognizes, however, that the NASA Earth science program must retain its flexibility to deal with the many shorter-term challenges and opportunities that arise over the course of a decade while community priorities are being implemented.

OTHER CONSIDERATIONS FOR FUTURE REVIEWS

As NASA proceeds with implementation of the current decadal survey mission portfolio, there are actions that the agency can perform now to prepare for future major programmatic reviews and priority-setting exercises. *The committee suggests that NASA work proactively to identify the potential for value-added international partnerships ahead of, and separately from, future programmatic reviews.* Similarly, opportunities to satisfy science objectives in non-traditional ways (e.g., constellation approaches, hosted payloads, suborbital campaigns) should be given due consideration. Such early preparatory work would help future committees and/or decision makers more easily identify synergies and potential cost savings as they craft a new mission queue.

[3]The CLARREO mission, for example, was recommended as a small mission and had grown to a large mission before being tabled for further formulation work prior to implementation.

6

Conclusions

The 2005 interim report of the Earth science and applications from space decadal survey discussed the importance of the U.S. civilian Earth observing system of environmental satellites and warned, "Today, this system of environmental satellites is at risk of collapse."[1] It went on to list a number of canceled, descoped, or delayed Earth observation missions. The 2007 decadal survey report warned in its preface that at the time of the report's release, this foundation was continuing to deteriorate because of descopes in the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and Geostationary Orbit Environmental Satellite-R Series programs and possible delay of the flagship Global Precipitation Measurement (GPM) mission.[2] In the time since the 2007 report's release, the anticipated program has eroded further because of significant budget shortfalls, the loss of two missions due to launch vehicle failures, changes in direction from the executive branch and Congress, and cost overruns on pre-decadal survey missions still in development.

Despite these challenges, NASA has continued to make substantial technical progress on the missions that were already in development at the time of the survey's release, including the successful launches of the Ocean Surface Topography mission in 2008 and Aquarius and the NPOESS Preparatory Project (NPP) in 2011. NASA has also effectively implemented decadal survey recommendations related to its new Earth Venture line of solicitations, the suborbital program, and the applied sciences program. Still, there is room for improvement. Improved coordination across missions and between disciplines is key to weathering this near-perfect storm of a decline in resources, increase in demands, and loss of heritage assets. Using realistic budget projections, the Earth science community cannot afford an all-encompassing program to enhance every aspect of Earth system science, nor can it afford collapse of the mission queue to save just a handful of missions. To this end, the committee reiterates the 2007 survey's call for a balanced set of capable Earth science missions rather than just a few missions that strive for perfection in limited disciplines.[3]

[1]National Research Council, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation,* The National Academies Press, Washington, D.C., 2005, p. 2.

[2]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

[3]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* 2007.

Appendixes

A

Statement of Task

The National Research Council shall convene an ad hoc committee to review the alignment of NASA's Earth Science Division's program with previous NRC advice, primarily the 2007 NRC decadal survey report, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.* The committee's review will describe:

- How well NASA's current program addresses the strategies, goals, and priorities outlined in the 2007 decadal survey and other relevant NRC reports;
- Progress toward realizing these strategies, goals and priorities; and
- In the context of current and forecast resources, any actions that could be taken to optimize the science value of the program.

The review should not revisit or alter the scientific priorities or mission recommendations provided in the decadal survey and related NRC reports, but may provide guidance about implementing the recommended mission portfolio in preparation for the next decadal survey.

B

Programmatic Decision Strategies and Rules from the Earth Science and Applications from Space 2007 Decadal Survey

The 2007 Earth science and applications from space decadal survey recognized that there are many risks and uncertainties in developing a suite of space missions, and it offered a number of programmatic guidelines and rules for guiding NASA and the National Oceanic and Atmospheric Administration to minimize these risks and protect the entire balanced program.[1] The rules outlined below largely duplicate those presented in the 2007 survey.

Leverage International Efforts

- Restructure or defer missions if international partners select missions that meet most of the measurement objectives of the recommended missions; then (1) through dialogue establish data-access agreements, and (2) establish science teams to use the data in support of the science and societal objectives.
- Where appropriate, offer cost-effective additions to international missions that help extend the values of those missions. These actions should yield significant information in the identified areas at substantially less cost to the partners.

Manage Technology Risk

- Sequence missions according to technological readiness and budget risk factors. The budget risk consideration may favor initiating lower-cost missions first. However, technology investments should be made across all recommended missions.
- Reduce cost risk on recommended missions by investing early in the technological challenges of the missions. If there are insufficient funds to execute the missions in the recommended time frames, it is still important to make advances on the key technological hurdles.
- Establish technology readiness through documented technology demonstrations before a mission's development phase, and certainly before mission confirmation.

[1]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., Box 3.4.

Respond to Budget Pressures and Shortfalls

- Delay downstream missions in the event of small (~10 percent) cost growth in mission development. Protect the overarching observational program by canceling missions that substantially overrun.
- Implement a system-wide independent review process that permits decisions regarding technical capabilities, cost, and schedule to be made in the context of the overarching science objectives. Programmatic decisions on potential delays or reductions in the capabilities of a particular mission could then be evaluated in light of the overall mission set and integrated requirements.
- Maintain a broad research program under significantly reduced agency funds by accepting greater mission risk rather than descoping missions and science requirements. Aggressively seek international and commercial partners to share mission costs. If necessary, eliminate specific missions related to a theme rather than whole themes.
- *In the event of large budget shortfalls,* re-evaluate the entire set of missions in light of an assessment of the current state of international global Earth observations, plans, needs, and opportunities. Seek advice from the broad community of Earth scientists and users and modify the long-term strategy (rather than dealing with one mission at a time). Maintain narrow, focused operational and sustained research programs rather than attempting to expand capabilities by accepting greater risk. Limit thematic scope and confine instrument capabilities to those well demonstrated by previous research instruments.

C

Applications of NASA's Earth Science Program

At the request of the committee, NASA provided the following examples (reprinted here as received) to illustrate societal benefits accruing from applications of NASA's Earth science program:

NASA-Developed and -Flown Thermal Infrared Sensor Measurements Used Operationally by States and Other Federal Agencies for Essential Water Monitoring

A NASA-developed and -built instrument, the Thermal Infrared Imager, flies on Landsats 5 and 7 and will be one of 2 instruments on the Landsat Data Continuity Mission (LDCM). No other satellite system provides the requisite thermal imagery required for water management in the western US. TIR measurements from these NASA-built research missions are used OPERATIONALLY by state agencies to monitor snowpack runoff and water consumption on a field-by-field basis in 9 western states (Nevada, Idaho, Wyoming, Montana, Colorado, New Mexico, Nebraska, North Dakota, and South Dakota). TIRS data have been called by State water managers the "Gold Standard" for cost-effective administration of water transfer agreements, and an "irreplaceable tool for western water managers." The data from the NASA-supplied instruments are indispensable for administering many USDA, Interior, and other federal water and land management programs. An Idaho Dept of Resources study notes that use of NASA Landsat thermal imagery "in lieu of expensive and problematic pump flow measurements, site visits, and electrical power consumption records" is estimated to save the western states $1B per decade in consumptive water monitoring costs. Landsats 5 and 7 are operated by the US Geological Survey, as will LDCM [be].[1]

MODIS Products Used by DoD During Operation Iraqi Freedom

Extreme weather conditions over southwest Asia posed significant challenges to military operations conducted during the 2003 Operation Iraqi Freedom (OIF) campaign. Improved environmental characterization from a suite of value-added NASA research satellite imagery from the Terra and Aqua platforms [was] made available to operational users in 2 to 3 hours turn-around time via a near real-time processing effort [involving] interagency collaboration between NASA, the National Oceanic and Atmospheric Administration (NOAA), and the Department of Defense (DoD).

NASA MODIS measurements were used to distinguish airborne dust from the surface and other atmospheric features, resulting in a revised enhancement useful in observing and tracking the dust storms frequent

[1]See http://landsat.gsfc.nasa.gov/news/news-archive/news_0069.html.

to southwest Asia. A post-deployment report from the USS Nimitz (CVN-68) noted, "The [MODIS-based] dust product was invaluable—we were able to track the progression of dust through southern Iraq and Kuwait. . . . We used model data in conjunction with the dust product to nail down the forecast in regards to the possibility of dust being advected to the [aircraft carrier]."

During OIF, MODIS fire products assisted analysts in monitoring the oil fields of southern Iraq for possible environmental sabotage (similar to what occurred during the 1991 Gulf War). Global fire products from MODIS, available to the public in near real-time via NASA sources, are being used operationally by a number of agencies including the United Nations Global Fire Monitoring Centre (GFMC) for monitoring, planning, and disaster mitigation.[2]

NASA Measurements Improve Volcanic Ash Advisories for Aircraft Routing and Safety

NASA-sponsored projects have demonstrated reliable and accurate detection of volcanic ash clouds using NASA Earth science satellites. The proven utility of this data led to its operational use by the NOAA National Weather Service to formulate Volcanic Ash Advisories. (These products were used extensively in the Iceland volcano in April 2010.) Recently, the NASA satellite data was used in volcanic ash advisories for aviators across the Gulf of Mexico due to the February 1 eruption of the Popocatepetl volcano in Mexico.[3]

NASA Measurements and Analyses Show Dust Deposits Darken Snow Over Large Regions and Accelerate Melt

NASA satellite observations have demonstrated how deposition of dust on western snowpack is leading to earlier snowmelt by 3-5 weeks in the Colorado River basin, resulting in a 3-week acceleration of the peak runoff period in Arizona. This is of vital importance to water managers and demonstrates essential linkages between atmospheric effects, radiation, and terrestrial processes including local and remote land use change.[4]

Forest and Timber Productivity Forecasting

A NASA-sponsored project applying Earth science satellite data and models indicates large-scale disturbance to western conifers by as early as 2020. Lodgepole pines, the backbone of the timber industry, will be gone from almost all of the Pacific Northwest by 2080 and replacement species (Douglas fir, Ponderosa pine, Larch) will likely be less productive.[5]

Impacts of Sea Level Rise on Coastal Communities (and NASA Facilities)

NASA Earth science researchers are applying satellite observations and modeling to assess impacts of climate change on NASA facilities to support risk management activities and adaptation. The first study [at] Kennedy Space Center indicates a 9-15 inch sea level rise by 2080 along the Space Coast. Overall, projections for the Space Coast indicate higher temperatures, fairly consistent annual precipitation, and rising sea levels.[6]

Electric and Gas Utilities Load Forecasting

A NASA-sponsored project is demonstrating improvements in short-term utility load forecasts by adding NASA Earth science data to the gas and electric utilities' existing load forecasting tools. The addition of NASA Earth science data allows the load forecast models to capture both microclimates and larger patterns across the service area and forecast load more accurately. Better load forecasts allow utilities to plan more

[2]Adapted from S.D. Miller, J.D. Hawkins, T.F. Lee, F.J. Turk, K. Richardson, A.P. Kuciauskas, J. Kent, R. Wade, C.E. Skupniewicz, J. Cornelius, J. O'Neal, et al., MODIS provides a satellite focus on Operation Iraqi Freedom, *International Journal of Remote Sensing* 27(7):1285-1296, 2006.

[3]For information on the use of NASA data by NOAA's Volcanic Ash Advisory Center, see http://www.ssd.noaa.gov/VAAC/washington.html and http://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/index.html.

[4]See http://geology.com/press-release/desert-dust-colorado-river/ and http://newsroom.ucla.edu/portal/ucla/dust-speeds-up-colorado-river-171804.aspx.

[5]See G. Hamilton, Climate change to drive lodgepole pine trees from B.C., *Vancouver Sun,* March 1, 2011; N.C. Coops and R.H. Waring, A process-based approach to estimate lodgepole pine (*Pinus contorta Dougl.*) distribution in the Pacific Northwest under climate change, *Climatic Change* 105:313-328, 2011.

[6]See Climate Adaptation Science Investigator Workgroup, *Adapting Now to a Changing Climate: Florida's Space Coast,* NASA Goddard Institute for Space Studies, New York, N.Y.

precisely in the 1-10 day timeframe, and improved load forecasts can save utilities money by reducing the swing volume they require.[7]

Flood Disaster Response (Australia and Pakistan)

NASA supported US disaster response efforts to Australia flooding earlier in 2011. NASA observations provided unique, daily observations of the flooding, which were used by several Australian agencies, including the Department of Transport and Main Roads, Dept. of Environment & Resource Management, and Geoscience Australia.[8]

The global coverage and technical capabilities of NASA Earth science satellites enabled NASA to perform flood mapping for Pakistan floods in late 2010. NASA investigators modified flood mapping algorithms to accommodate the extremely high sediment concentrations of those floods. NASA's products were added to those provided to disaster responders, relief agencies, and aid providers, including the International Red Cross/Red Crescent, World Bank, World Food Programme, and US military.[9]

New Map Offers a Global View of Health-Sapping Air Pollution

In many developing countries, the absence of surface-based air pollution sensors makes it difficult, and in some cases impossible, to get even a rough estimate of the abundance of a subcategory of airborne particles that epidemiologists suspect contributes to millions of premature deaths each year. The problematic particles, called fine particulate matter (PM2.5), are 2.5 micrometers or less in diameter, about a tenth the [diameter of a] human hair. These small particles can get past the body's normal defenses and penetrate deep into the lungs.

To fill in these gaps in surface-based PM2.5 measurements, experts look toward satellites to provide a global perspective. Yet, satellite instruments have generally struggled to achieve accurate measurements of the particles in near-surface air. The problem: Most satellite instruments can't distinguish particles close to the ground from those high in the atmosphere. In addition, clouds tend to obscure the view. And bright land surfaces, such as snow, desert sand, and those found in certain urban areas, can mar measurements.

However, the view got a bit clearer this summer with the publication of the first long-term global map of PM2.5 in a recent issue of *Environmental Health Perspectives*. Canadian researchers Aaron van Donkelaar and Randall Martin at Dalhousie University, Halifax, Nova Scotia, Canada, created the map by blending total-column aerosol amount measurements from two NASA satellite instruments with information about the vertical distribution of aerosols from a computer model.[10]

Observing Recovery at Mt. St. Helens

NASA has helped document recovery of the Mt. St. Helen's area [from] the volcanic eruption (1980) by showing how the distribution of vegetation has recovered over a 30 year period. In the three decades since the eruption, Mt. St. Helens has given scientists an unprecedented opportunity to witness the intricate steps through which life reclaims a devastated landscape. The scale of the eruption and the beginning of reclamation in the Mt. St. Helens blast zone are documented in this series of images captured by NASA's Landsat series of satellites between 1979 and 2010.[11]

NASA Demonstrates Tsunami Prediction System

A NASA-led research team has successfully demonstrated for the first time elements of a prototype tsunami prediction system that quickly and accurately assesses large earthquakes and estimates the size of resulting tsunamis.

[7]See http://appliedsciences.nasa.gov/pdf/FinalHighlightsfor23Nov09.pdf and http://www.thebaynet.com/news/index.cfm/fa/viewstory/story_ID/15694.

[8]See http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=48524 and http://www.nasa.gov/mission_pages/hurricanes/archives/2011/h2011_Yasi.html.

[9]See http://www.nasa.gov/topics/earth/features/flood20100820.html and http://blogs.nasa.gov/cm/blog/whatonearth/posts/post_1288240080113.html.

[10]"New Map Offers a Global View of Health-Sapping Air Pollution," published online by NASA on 09/22/2010; available at http://www.nasa.gov/topics/earth/features/health-sapping.html.

[11]See http://earthobservatory.nasa.gov/Features/WorldOfChange/sthelens.php.

After the magnitude 8.8 Chilean earthquake on Feb. 27, a team led by Y. Tony Song of NASA's Jet Propulsion Laboratory in Pasadena, Calif., used real-time data from the agency's Global Differential GPS (GDGPS) network to successfully predict the size of the resulting tsunami. The network, managed by JPL, combines global and regional real-time data from hundreds of GPS sites and estimates their positions every second. It can detect ground motions as small as a few centimeters.

"This successful test demonstrates that coastal GPS systems can effectively be used to predict the size of tsunamis," said Song. "This could allow responsible agencies to issue better warnings that can save lives and reduce false alarms that can unnecessarily disturb the lives of coastal residents."[12]

U.S. Navy Use of NASA MODIS Aerosol Observations

Aerosol optical depth data from NASA's MODIS satellite are being operationally assimilated into the numerical model of the US Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC), improving model performance two days out.[13]

NASA, Japan Release Most Complete Topographic Map of Earth

NASA and Japan released a new digital topographic map of Earth that covers more of our planet than ever before. The map was produced with detailed measurements from NASA's Terra spacecraft.

The new global digital elevation model of Earth was created from nearly 1.3 million individual stereo-pair images collected by the Japanese Advanced Spaceborne Thermal Emission and Reflection Radiometer, or Aster, instrument aboard Terra. NASA and Japan's Ministry of Economy, Trade and Industry, known as METI, developed the data set. It is available online to users everywhere at no cost.

The Digital Elevation Model from the joint Japanese ASTER instrument aboard NASA's Terra spacecraft was made publicly available through NASA's Land Processes Distributed Active Archive Center (operated for NASA by USGS), which within a few months had distributed data to over 30,000 users (and with so much short-term demand that the data center computers crashed within 24 hours of [the] release).[14]

NASA Data Reveal Major Groundwater Loss in California

Data from NASA's GRACE satellite mission have documented the seasonal and interannual variability of total water storage in the Sacramento and San Joaquin drainage basins, including how agricultural use is affecting water storage.[15]

NASA Improving Short-Term Weather Prediction by the National Weather Service

NASA satellite data are [being] routinely used by operational weather forecasters in the Southern region of the US National Weather Service through the Short-Term Prediction Research and Transition (SPoRT) [center] in Huntsville, AL.

"It's not just a matter of them throwing random data sets over the fence to us and hoping we might be able to use them," says Chris Darden from the National Weather Service (NWS). "They work with us to figure out precisely what we need. Then they put that data into a format we can read, actually integrating it with our radar displays. And they train us to understand and interpret the information they give us."[16]

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[12]See http://www.nasa.gov/home/hqnews/2010/jun/HQ_10-139_Tsunami_Prediction_System.html.

[13]See http://www.atmos-chem-phys.org/11/557/2011/acp-11-557-2011.pdf.

[14]See http://www.nasa.gov/topics/earth/features/aster-20090629.html; http://asterweb.jpl.nasa.gov/gdem.asp.

[15]See http://www.jpl.nasa.gov/news/news.cfm?release=2009-194.

[16]*NASA Science News,* April 22, 2009, available at http://science.nasa.gov/science-news/science-at-nasa/2009/22apr_severe weather/.

D

NOAA Satellite Programs

The 2007 Earth science and applications from space decadal survey offered several important recommendations for the National Oceanic and Atmospheric Administration (NOAA).[1] The first set consisted of recommendations related to the NPP, NPOESS, and GOES-R missions (pp. 5-6, table and footnotes omitted):[2]

> ***Recommendation:*** **NOAA should restore several key climate, environmental, and weather observation capabilities to its planned NPOESS and GOES-R missions; namely:**
>
> - **Measurements of ocean vector winds and all-weather sea-surface temperatures descoped from the NPOESS C1 launch should be restored to provide continuity until the CMIS replacement is operational on NPOESS C2 and higher-quality active scatterometer measurements (from XOVWM, described in Table ES.1) can be undertaken later in the next decade.**
> - **The limb sounding capability of the Ozone Monitoring and Profiling Suite (OMPS) on NPOESS should be restored.**
>
> **The committee also recommends that NOAA:**
>
> - **Ensure the continuity of measurements of Earth's radiation budget (ERB) and total solar irradiance (TSI) through the period when the NPOESS spacecraft will be in orbit by:**
>
>   **—Incorporating on the NPOESS Preparatory Project (NPP) spacecraft the existing "spare" CERES instrument, and, if possible, a TSI sensor, and;**
>   **—Incorporating these or similar instruments on the NPOESS spacecraft that will follow NPP, or ensuring that measurements of TSI and ERB are obtained by other means.**

[1]National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.
[2]Note that acronyms not defined in the text are defined in Appendix G.

- **Develop a strategy to restore the previously planned capability to make high temporal and vertical-resolution measurements of temperature and water vapor from geosynchronous orbit**.

The high-temporal- and high-vertical-resolution measurements of temperature and water vapor from geosynchronous orbit were originally to be delivered by the Hyperspectral Environmental Sensor (HES) on the GOES-R spacecraft. Recognizing the technological challenges and accompanying potential for growth in acquisition costs for HES, the committee recommends consideration of the following approaches:

- **Working with NASA, complete the GIFTS instrument, deliver it to orbit via a cost-effective launch and spacecraft opportunity, and evaluate its potential to be a prototype for the HES instrument, and/or**
- **Extend the HES study contracts focusing on cost-effective approaches to achieving essential sounding capabilities to be flown in the GOES-R time frame**.

The second set of recommendations pertained to transitions from research to operations (p. 8, table omitted):

- **NOAA should transition to operations three research observations. These are vector sea surface winds, GPS radio occultation temperature, water vapor, and electron density sounders; and total solar irradiance (restored to NPOESS). Approaches to these transitions are provided through the recommended XOVWM, GPSRO, and CLARREO missions listed in Table ES.1.**

PROGRESS ON THE IMPLEMENTATION OF THE DECADAL SURVEY RECOMMENDATIONS AND OTHER NOAA SATELLITE PROGRAMS

NOAA satellite programs continue to be impacted by budget shortfalls and financial burdens associated with the NPOESS, now JPSS, program. In particular, the President's request for JPSS for FY2011 was $1.07 billion, yet Congress appropriated less than $400 million, a shortfall of more than $700 million. As NOAA struggles to implement JPSS in time to avoid a potential gap in measurements from the currently operating instruments that provide data used to support numerical weather prediction, other NOAA satellite programs and the 2007 decadal survey's recommended missions are being delayed or canceled. Details on the NOAA satellite program follow.

UPDATE ON RESTORATION OF NPOESS CLIMATE SENSORS

In June 2006, as a consequence of the Nunn-McCurdy review by the DOD (required by the Congress because of a projected overrun greater than 25 percent), a restructured NPOESS program was announced that did not include a number of climate sensors.[3] In early 2010, the joint DOD/NOAA/NASA NPOESS program was canceled in favor of returning to the pre-NPOESS plan of having separate DOD and NOAA polar orbiting weather satellite programs, namely NOAA's Joint Polar Satellite System (JPSS) and DOD's Defense Weather Satellite System (DWSS). Described briefly below is the status, as of late January 2012, of the climate sensors that were "demanifested" from NPOESS:

- *Aerosol Polarimetry Sensor (APS).* APS was planned to fly on NASA's Glory mission in 2011; however, the Taurus XL launch vehicle being used to launch Glory failed to provide the proper separation of the launch vehicle fairing, resulting in the loss of the mission.

[3]National Research Council, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring,* The National Academies Press, Washington, D.C., 2008.

- *Total Solar Irradiance Sensor (TSIS).* A Total Irradiance Monitor (TIM) to measure total solar irradiance was manifested on Glory, and thus was lost as well. In the meantime NASA's SORCE mission continues to provide TIM data (and spectrally resolved irradiance via the SSI instrument). Launched in January 2003 and currently in its fourth year of extended-phase operations, the spacecraft is powered by batteries that are believed to be the life-limiting factor for the mission.[4] NASA thinks that a work-around for a recent spacecraft battery problem could allow SORCE to continue to operate through 2014;[5] however, a gap in the TIM record, which extends from 1978, is still likely, absent launch of a free-flyer mission or manifesting of a TIM on another spacecraft that could launch in this time frame. NOAA is examining options for accelerating the flight of TSIS, currently in development at LASP, by flying it as part of the JPSS free-flyer program.[6] Unfortunately, because of FY2011 budget limitations, there are currently no identified funds for the flight of TSIS. A broad-band radiometer was also recommended for the decadal survey's CLARREO mission, but with cost estimates having grown by a factor of 3, NASA has deferred the mission indefinitely.
- *OMPS (Ozone Monitoring and Profiling Suite)-Limb.* NPP (launched October 28, 2011) is flying both the OMPS Nadir and the OMPS Limb Suite. Unfortunately, JPSS-1 will carry only the OMPS Nadir instrument. Resumption of the flight of the OMPS Limb sensor is planned for JPSS-2, but not until 2019 or later.
- *Earth Radiation Budget Sensor (ERBS).* CERES (Clouds and the Earth's Radiant Energy System) sensor FM 5 is also on NPP. CERES FM 6 is planned for flight on JPSS-1 in 2017. ERBS is planned as a CERES follow-on to be flown as part of the JPSS free-flyer program. Unfortunately, as for TSIS, in the FY2011 and FY2012 budgets there are no funds identified for the flight of ERBS.
- *Altimeter (ALT).* The ocean altimeter instrument, ALT, which had been planned for inclusion on NPOESS (now JPSS), was canceled ("demanifested) in 2006 as a result of the program review and revisions that occurred as part of NPOESS's "Nunn-McCurdy" certification.[7] However, in a bit of a success story, at least through Jason-2, the research-oriented NASA/CNES TOPEX/Poseidon mission has gradually evolved into an international operational program. TOPEX/Poseidon was follow by Jason, which in turn has been followed by the currently operating Ocean Surface Topography Mission (OSTM) on the Jason-2 satellite. Plans are in place by NOAA/EUMETSAT/NASA/CNES to fly Jason-3; however, the possibility of substantial delays is threatening this mission (see Jason-3, below).
- *NPOESS to JPSS on the civil side.* As already noted, the DOD/NOAA/NASA NPOESS program was canceled in early 2010. What emerged in its place on the civil (NOAA) side was JPSS, a NOAA polar orbiting weather satellite program to be implemented by NASA. NOAA had planned for JPSS-1 to fly in 2014, to be followed by JPSS-2 in 2018; NOAA also assumed that a free-flyer element to JPSS would allow for the flight of key displaced NPOESS climate sensors as discussed above. However, as a result of a continuing resolution that limited FY2011 budgets to those in FY2010, a planned $1.06 billion in FY2011 for JPSS was appropriated at only $382 million. This large funding shortfall appears likely to delay the planned launch of JPSS-1 to at least 2017.

Given the program's limited funding, the first priority has been to keep NPP on track. Originally planned as a mission to demonstrate all the new NPOESS instrument technologies, companion algorithms, and data-processing approaches, NPP is now being pressed into service as a full-fledged operational element of the new JPSS program to help cope with the extensive delays that had occurred in the NPOESS program

[4]See "SORCE Extended Mission Proposal Submitted," in *Solar Radiation and Climate Experiment Monthly Newsletter*, February-March 2011, available at http://lasp.colorado.edu/sorce/news/news_letter.htm.

[5]Ibid.

[6]As this report went to press, NOAA and the Air Force were examining the possibility of flying a backup TIM from the SORCE program as a hosted payload.

[7]Nunn-McCurdy certification is discussed in National Research Council, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft,* 2008. For a specific discussion on ALT, see pp. 35-38.

as well as the more recent delays to the JPSS program. However, a recent NASA inspector general report has called into question the integrity of some of the NPP instruments, including VIIRS and CrIS, and has projected that, owing to their development in an undisciplined environment, i.e., under the guidance of the NPOESS Integrated Program Office (IPO), these instruments might last only 3 years, rather than the planned 7 years, further exacerbating the overall NPOESS to JPSS situation.

- *Ocean Vector Winds (XOVWM in the decadal survey).* Budget problems have affected NOAA's capability to implement the 2007 survey's recommendation to develop and launch a next-generation dual-frequency scatterometer to measure ocean vector winds (XOVWM). XOVWM would have continued and enhanced the measurement capabilities of NASA's QuikSCAT spacecraft, which operated nominally from 1999 to 2009.[8] Although developed as a NASA research mission, QuikSCAT supplied data that proved of great utility and were routinely assimilated into numerical weather forecast models.

Realizing that the XOVWM instrument was not affordable in the near term, NOAA initially planned to develop a less-capable version of the XOVWM (the DFS, or dual-frequency scatterometer) for accommodation on the Japanese GCOM-W2 spacecraft, which is scheduled for launch in 2016. However, in late 2010, NOAA recognized that future budgets would not support this effort and on January 13, 2011, the agency sent a letter to NASA stating that pursuit of the NOAA DFS on GCOM-W2 would be unaffordable in the foreseeable future. Further, NOAA has proposed that responsibility for the provision of operational scatterometry data be shifted to NASA. In the meantime, NOAA is working with NASA and the Indian space agency, ISRO, to acquire timely access to ocean surface vector wind data from the ISRO Oceansat-2 satellite.

- *GOES-R/HES.* In this case, NOAA conducted an analysis of alternatives (AoA) for the capabilities planned for the Hyperspectral Environmental Suite (HES). The AoA recommended flying a sounder-only capability in the GOES-R time frame (but not on GOES-R). Limited budget and other higher-priority NWS priorities have made this option not feasible at this time. It is particularly ironic, given the cost of GOES-R missions, that none of them is planned to have a sounder capability, even though their predecessor missions, i.e., GOES-I through GOES-P (8 missions), all had a sounding capability.

- *Jason-3.* Precise measurements of sea-surface topography, which have proved to be among the most useful measurements for ocean and climate science, began in1992 with the launch of the NASA/CNES (France) TOPEX/Poseidon spacecraft. TOPEX/Poseidon was followed by the Jason-1 mission, launched in 2001, and Jason-2/OSTM, which was launched in 2008.[9]

Extension of this critical data record was planned via the launch of Jason-3 in 2014. Jason-3 enjoyed the strong support of both the United States and its European partner, EUMETSAT. However, the FY2011 budget reduced funding on the NOAA side, and the proposed NOAA FY2012 Jason-3 budget is threatened as well, with the result that discussions are underway between EUMETSAT and NOAA that could result in a 1- to 2-year delay for Jason-3. Additionally, the two recent Taurus XL failures (Orbiting Carbon Observatory and Glory) may delay the decision on a launch vehicle for Jason-3, further delaying the program, increasing costs, and threatening the continuity of this critically important long-term climate data record.

- *COSMIC-2 (GPSRO in the decadal survey).* Observations from the six-satellite constellation COSMIC launch in 2006 and the GPS radio occultation (RO) sensor on METOP-A have demonstrated the value of RO observations for weather prediction, space weather, and climate, providing bias-free profiles of refractivity (temperature and water vapor) in the troposphere, temperature in the stratosphere, and elec-

[8]The QuikSCAT mission continues to operate; however, the instrument's antenna ceased spinning. The mission now plays a key role in calibrating the ISRO scatterometer and was strongly endorsed for continuation by the 2011 NASA Earth Science Senior Review process, with the applications subpanel ranking the mission as "high utility" despite the loss of antenna rotation. See http://nasascience.nasa.gov/earth-science/missions/operating/.

[9]While the TOPEX/Poseidon and Jason-1 missions were collaborations between NASA and the French space agency CNES, OSTM is a four-partner mission with NASA, CNES, EUMETSAT, and NOAA. See http://sealevel.jpl.nasa.gov/files/ostm/Spacecraft-OSTM_Fact_Sheet_Final.pdf.

tron density in the ionosphere.[10] NOAA has been working with the U.S. Air Force and Taiwan to develop a follow-on mission to COSMIC (which is nearing the end of its lifetime in 2012) called COSMIC-2 (C-2). C-2 would consist of a 12-satellite constellation to be launched beginning in 2015. The Air Force is making excellent progress on developing space-weather sensors and on engineering studies. Taiwan has committed to partner with NOAA on C-2 and has its funding appropriated, but NOAA has yet to commit even very modest funds for an official start. The President's budget for FY2011 included a $3.7 million NOAA start, but after months of a continuing resolution Congress finally passed a budget without these funds. The President's FY2012 budget contained $11.3 million for COSMIC-2, but the FY2012 appropriation did not contain any funds for a C-2 start. The estimated total cost for C-2 is $410 million, with Taiwan, NOAA, and the U.S. Air Force sharing the costs roughly equally. In early 2012, after this report was completed, the Air Force announced that it would fund at least six of the payloads for COSMIC-2 and provide a launch.

- *DSCOVR (Deep Space Climate Observatory).* Although the Deep Space Climate Observatory was not a priority in the Earth science and applications from space decadal survey,[11] the NOAA FY2011 budget request had $9.5 million for DSCOVR's refurbishment, and the FY2012 request was $47.3 million. DSCOVR will be launched into an orbit around the L1 libration point, a stable gravity-neutral point approximately 1 million miles from Earth. From that location, sensors on DSCOVR would have a constant view of the day side of Earth. More commonly used for solar science investigations, the L1 libration point is an ideal vantage from which a spacecraft can monitor space weather and warn of solar storms before they hit Earth. NOAA did not receive funding for DSCOVR in FY2011; however, the FY2012 enacted budget provided $29.8 million. The U.S. Air Force will pay for the launch of DSCOVR, which is expected in 2014.[12]
- *CLARREO.* A broad-band radiometer was also recommended in the 2007 decadal survey for the CLARREO mission, but the mission was put on hold in the FY2011 budget cycle.

CLIMATE DATA RECORDS

As noted in *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft,*[13] there are structural problems associated with the provision of climate-quality measurements from systems designed to meet national objectives more closely associated with the needs of the operational weather forecast community. At the time of the 2007 decadal survey, NPOESS lacked a transparent program for monitoring sensor calibration and performance and for verifying the products of analysis algorithms. Moreover, it lacked the direct involvement of scientists who have played a fundamental role in developing climate-quality records from spaceborne observations. Since then, NOAA has made a major commitment to scientific-data stewardship. NOAA has developed a strategy to provide for the essential characterization, calibration, stability, continuity, and data systems required to support climate applications for climate variables such as sea-surface temperature. NOAA's National Climatic Data Center has made development of climate data records a high priority. This approach is consistent with and responsive to many NRC reports that indicate that the generation of climate data records requires considerable scientific insight, including the blending of multiple sources of data; error analysis; and access to raw data.

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[10] See http://www.atmos-meas-tech.net/4/1077/2011/amt-4-1077-2011.html.

[11] The 2007 decadal survey did note that DSCOVR instruments would provide an operational solar wind monitor at L1, a high priority for the solar and space physics community. See National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics,* The National Academies Press, Washington, D.C., 2003.

[12] The President's requested budget for FY2013 was released to the public on February 13, 2012, after the present report was completed. Funding for DSCOVR of $22,883,000 is requested in the NOAA NESDIS budget. Assuming that the program is adequately funded, and with Air Force support for the launch vehicle, DSCOVR would be ready for launch in 2014.

[13] National Research Council, *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft,* 2008.

E

NASA's Responses to the 2007 Decadal Survey and Its April 2011 Status Update

This appendix lists each of the recommendations in the 2007 Earth science and applications from space decadal survey (National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007) and NASA's response to the report provided to the Space Studies Board in 2009, with updates from NASA given to the Committee on the Assessment of NASA's Earth Science Program at its first meeting on April 28, 2011. *The text in Table E.1 is taken verbatim from the three documents. Page numbers following each statement refer to the location of the statement in the document from which it came.*

TABLE E.1 Recommendations from the 2007 Decadal Survey and NASA Responses in 2009 and 2011

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
***Recommendation:* The U.S. government, working in concert with the private sector, academe, the public, and its international partners, should renew its investment in Earth-observing systems and restore its leadership in Earth science and applications.** (p. 2)	The committee predicated its schedules and program on a NASA ESD budget that reached the level of $2B/year (approximately equal to the FY2000 level) in 2010. The Obama administration's FY2010 budget for NASA ESD is $1.405B exclusive of carry-over funds from the 2009 American Recovery and Reinvestment Act), increasing steadily by about $50M/year thereafter. (p. 2)	The decadal survey predicated its schedules and program on a NASA ESD budget that reached the level of $2 billion/year [FY2006 $] in FY2010 (approximately equal to the FY2000 level). ESD has focused resources on the development and rapid launch of Foundational Missions (pre-decadal survey: OSTM, OCO, Glory, NPP, LDCM, GPM and added decadal survey-recommended actions, including serving in international leadership/coordination roles. (p. 3)
Between 2006 and the end of the decade, the number of operating missions will decrease dramatically, and the number of operating sensors and instruments on NASA spacecraft, most of which are well past their nominal lifetimes, will decrease by some 40 percent (see Figures ES.1 and ES.2). . . . Among the many measurements expected to cease over the next few years, the committee has identified several that are providing critical information now and that need to be sustained into the next decade—both to continue important time series and to provide the foundation necessary for the recommended future observations. These include measurements of total solar irradiance and Earth radiation and vector sea-surface winds; limb sounding of ozone profiles; and temperature and water vapor soundings from geostationary and polar orbits. (p. 3)	While it is true that 14 of the 15 operating NASA research missions are or soon (within a year) will be beyond their design lives—and in some cases (e.g., QuikSCAT) have been operating for more than 3 times their design lives, the 2009 Senior Review assessed the technical status of each mission and noted that only ICESAT-1 was expected to become scientifically useless prior to 2012. The decadal survey committee observation is valid, however, in that many of these satellites in extended mission have suffered partial failures in redundant systems, and are thus down to single-string operations. (p. 2)	At present (April 2011)—of the 13 operating missions at the time of the decadal survey: — 12 missions continue to operate substantially as designed — ICESAT-1 was terminated owing to laser failure (beyond design life) — QuikSCAT operates, but not in wind mode (antenna; beyond design life) — Cloudsat is experiencing significant battery issues (beyond design life) — GRACE is experiencing battery issues (beyond design life) — Landsat-7 quality degraded (beyond design life) — 2011 Sr. Review is ongoing and will report out in June, 2011 — OSTM/Jason-2 successfully launched and operating — OCO, Glory launch vehicle failures (p. 5)
***Recommendation:* NOAA should restore several key climate, environmental, and weather observation capabilities to its planned NPOESS and GOES-R missions, namely:**		

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
• **Measurements of ocean vector winds and all-weather sea-surface temperatures descoped from the NPOESS C1 launch should be restored to provide continuity until the CMIS replacement is operational on NPOESS C2 and higher-quality active scatterometer measurements (from XOVWM, described in Table ES.1) can be undertaken later in the next decade.** (p. 5)	NOAA, with NASA reimbursable support (and starting in FY2010, NASA co-funding) has engaged in detailed design studies and international negotiations with JAXA to provide a vector wind measurement capability (dual-frequency scatterometer) to fly on the JAXA GCOM-W2 mission, scheduled to launch Net 2015. NOAA, with communication with NASA, is working with JAXA to negotiate near-real-time provision by JAXA of microwave radiometer measurements from the AMSR-Follow-On instruments on GCOM-W1 (11/2011 to 3/2012 LRD) and GCOM-W2, to continue the availability to the United States of all-weather SST measurements such as those initiated by the AMSR-E instrument on Aqua. The same negotiations cover near-real-time access to the vector wind measurements from a NOAA-supplied Dual-Frequency Scatterometer instrument for GCOM-W2. (p. 3)	NOAA, with NASA reimbursable support has engaged in detailed design studies and international negotiations with JAXA to provide a vector wind measurement capability (dual-frequency scatterometer) to fly on the JAXA GCOM-W2 mission, scheduled to launch NET 2015. In January 2011, NOAA informed NASA that it would not be able to support continued studies or future implementation of a scatterometer, but that NOAA would welcome NASA provision of NRT data from a research-based instrument. NASA discussions are ongoing with OSTP and OMB. NASA and NOAA collaborate in joint discussions with ISRO for access to, and refinements of, Oceansat-2 scatterometer and ocean color data. (p. 38)
• **The limb sounding capability of the Ozone Monitoring and Profiling Suite (OMPS) on NPOESS should be restored.** (p. 5)	NOAA and NASA co-funded the restoration of limb-sounding capability to the OMPS instrument package on NPP, and this has been completed. Ozone profiling through limb-sounding capability for NPOESS remains an open issue for NOAA. (p. 3)	NOAA and NASA co-funded the restoration of limb-sounding capability to the OMPS instrument package on NPP, and this has been completed. Ozone profiling through limb-sounding capability for JPSS remains an open issue for NOAA. (p. 39)
The committee also recommends that NOAA: • **Ensure the continuity of measurements of Earth's radiation budget (ERB) and total solar irradiance (TSI) through the period when the NPOESS spacecraft will be in orbit by:**		
—Incorporating on the NPOESS Preparatory Project (NPP) spacecraft the existing "spare" CERES instrument, and, if possible, a TSI sensor. (p. 5)	NOAA reimbursable funding has been used by NASA to refurbish, test, and integrate the CERES FM-5 spare unit onto NPP. This task was completed less than 18 months after the decision to proceed. A TSI capability is not needed on NPP, as the NASA Glory mission, now due to launch NLT 11/2010 carries a state-of-the-art Total Irradiance Monitor instrument, and the recent NASA ESD Senior Review extended the ongoing SORCE mission (ACRIMSAT was also conditionally extended). (p. 3)	NOAA reimbursable funding has been used by NASA to refurbish, test, and integrate the CERES FM-5 spare unit onto NPP. This task was completed in less than 18 months after ATP. A TSI capability is not thought to be needed on NPP, as the NASA Glory Mission carried a state-of-the-art TIM instrument, and the 2009 NASA ESD Senior Review extended the ongoing SORCE mission (ACRIMSAT was also conditionally extended). (p. 40)

continues

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
—Incorporating these or similar instruments on the NPOESS spacecraft that will follow NPP, or ensuring that measurements of TSI and ERB are obtained by other means. (p. 5)	NOAA reimbursable funding has recently been made available to NASA for construction of the CERES FM-6 and TSIS instruments for flight on the NPOESS C-1 mission. (p. 4)	NOAA reimbursable funding has recently been made available to NASA for construction of the CERES FM-6 and TSIS instruments for flight on TBD missions. (p. 40)
• **Develop a strategy to restore the previously planned capability to make high-temporal- and high-vertical-resolution measurements of temperature and water vapor from geosynchronous orbit.** (p. 5)	NASA is not aware of NOAA plans to develop these capabilities. (p. 4)	NOAA has not approached NASA with any plans for implementing a flight unit based on the existing GIFTS Engineering Development Unit, or any other approach. NASA has provided written statements of its willingness to consider a proposal for a Space Act agreement to enable further development of the GIFTS EDU. (p. 41)
The high-temporal- and high-vertical-resolution measurements of temperature and water vapor from geosynchronous orbit were originally to be delivered by the Hyperspectral Environmental Sensor (HES) on the GOES-R spacecraft. Recognizing the technological challenges and accompanying potential for growth in acquisition costs for HES, the committee recommends consideration of the following approaches:		
• **Working with NASA, complete the GIFTS instrument, deliver it to orbit via a cost-effective launch and spacecraft opportunity, and evaluate its potential to be a prototype for the HES instrument.** (p. 6)	NOAA has not approached NASA with any plans or discussions of implementing a flight unit based on the existing GIFTS Engineering Development Unit (EDU), or any other approach. NASA has provided written statements of its willingness to consider a proposal for a Space Act agreement to enable further development of the GIFTS EDU. (p. 4)	NOAA has not approached NASA with any plans for implementing a flight unit based on the existing GIFTS Engineering Development Unit, or any other approach. NASA has provided written statements of its willingness to consider a proposal for a Space Act agreement to enable further development of the GIFTS EDU. (p. 41)
• **Extend the HES study contracts focusing on cost-effective approaches to achieving essential sounding capabilities to be flown in the GOES-R time frame.** (p. 6)	NASA is not aware of the status of any NOAA continuations of the HES study contracts. (p. 4)	NASA is not aware of the status of any NOAA continuations of the HES study contracts. (p. 41)
Recommendation: **NASA should ensure continuity of measurements of precipitation and land cover by:**		

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
Launching the GPM mission in or before 2012. (p. 6)	GPM continues on track for a launch of the GPM Core mission, in collaboration with JAXA (who provides the HII-A L/V and the Dual-Frequency Precipitation Radar), in 7/2013. GPM will complete its mission CDR [Critical Design Review] and [Key Decision Point] KDP-C reviews in September, 2009. Cost increases and 70% budgeting requirements have caused the planned GPM Low Inclination Orbiter (LIO) mission to be put on hold, pending negotiations with international partners. However, the NASA budget DOES continue to include procurement of the second GMI-2 radiometer instrument (the sole science instrument planned for LIO), accommodation costs should a partner spacecraft and launch be identified, and all necessary space and ground telemetry and science funding to cover a replacement LIO mission. (pp. 4-5)	GPM continues on track for a launch of the GPM Core mission, in collaboration with JAXA, in 7/2013. GPM passed its KDP-C in 12/2009. Cost increases and 70% budgeting requirements caused the planned GPM Low Inclination Orbiter (LIO) mission to be put on hold, pending negotiations with international partners (NASA continued to budget for and develop the GMI-2 instrument, accommodation costs, data downlink, and science). The President's FY2012 budget directs termination of all GPM LOI activities. (p. 7)
• **Securing before 2012 a replacement for collection of Landsat 7 data.** (p. 6) **The committee also recommends that NASA continue to seek cost-effective, innovative means for obtaining information on land cover change.** (p. 6)	LDCM continues toward a 12/2012 LRD, carrying both the OLI (30m resolution multispectral instrument) and a QWIPS technology Thermal Infrared Sensor ("TIRS"; 120 m-resolution). Instrument PDRs have been successfully completed; Mission PDR was held in July 2009 in preparation for KDP-C review in November. OLI, s/c, and launch vehicle contracts are in place. TIRS is an in-house GSFC implementation. USGS is facing significant budget challenges for the LDCM Mission Operations Element contract/development (NASA procurement, using reimbursable funding from USGS). (p. 5)	LDCM continues on-track toward a 12/2012 LRD, carrying both the OLI and a Thermal Infrared Sensor ("TIRS"; 120 m-resolution—TIRS was mandated but not funded by Congress, leading to ~$150 million hit to the ESD core program). LDCM passed its KDP-C in December, 2009. TIRS is an in-house GSFC development. Residual mission development risk is being focused on TIRS, to ensure a 12/2012 launch of LDCM with at least a full baseline OLI mission. Significant launch vehicle (Atlas-V) penalties (up to ~$150 million) will be incurred should the launch be delayed by NASA. NASA continues to work with USGS to accommodate USGS funding issues for the LDCM Mission Operations Element contract/development (MOE is a NASA procurement, using reimbursable funding from USGS). SMD/JASD working with USGS for reimbursable Landsat 9 program. (p. 8)

continues

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
Recommendation: **In addition to implementing the re-baselined NPOESS and GOES program and completing research missions currently in development, NASA and NOAA should undertake the set of 17 missions recommended in Tables ES.1 and ES.2 comprising low-cost (<$300 million), medium-cost ($300 million to $600 million), and large-cost ($600 million to $900 million) missions and phased appropriately over the next decade. Larger, facility-class (>$1 billion) missions are not recommended. As part of this strategy:** (p. 8)	NASA concept and formulation studies indicate that the decadal survey mission cost estimates are understated by factors of 2-6 (for instance, CLARREO [10 instruments on 3 separate spacecraft] was estimated by the survey at a total mission cost of $200 million, vs. ~$950 million in the NASA pre-formulation studies). NASA faces considerable uncertainty in the availability of medium-class launch vehicles beyond 2011 due to the retirement of the Delta-II. The availability of new commercial launch vehicles in this class will influence the implementation of future mission architectures. (p. 5)	NASA concept, pre-formulation, and formulation studies indicate that the decadal survey's mission cost estimates were understated by factors of 2-6. (p. 9)
NOAA should transition to operations three research observations. These are vector sea-surface winds; GPS radio occultation temperature, water vapor, and electron density soundings; and total solar irradiance (restored to NPOESS). Approaches to these transitions are provided through the recommended XOVWM, GPSRO, and CLARREO missions listed in Table ES.1. (p. 8)	Recommendations to NOAA. Note discussion above on CERES and scatterometer capabilities being planned or funded by NOAA for NPOESS C-1. NOAA international discussions regarding GPSRO are in an early stage. (p. 5)	Recommendations to NOAA. Note discussion above on CERES and scatterometer capabilities being planned or funded by NOAA for JPSS. NOAA international discussions regarding GPSRO are in an early stage. (p. 42)
NASA should implement a set of 15 missions phased over the next decade. All of the appropriate low Earth orbit (LEO) missions should include a Global Positioning System (GPS) receiver to augment operational measurements of temperature and water vapor. The missions and their specifications are listed in Table ES.2. (p. 8)	SMAP entered formulation in 9/2008; ICESat-2 will enter formulation in late 2009. Competitive science teams have been solicited (through ROSES) and selected for both SMAP and ICESAT-2 in late summer 2008. Budgetary-driven LRDs for SMAP and ICESAT-2 are 2014 and 2015, respectively. Strong (>$10 million/year) ongoing pre-formulation science and technical studies are being conducted for DESDynI and CLARREO; in March, 2009, after nearly a year of study, the decision was made by ESD to implement DESDynI as 2 spacecraft (a radar and a lidar), to launch within 1 year of each other. Budgetary-driven LRDs for CLARREO and DESDynI are 2019-2020 (for both). Community and international workshops have been held (often multiple workshops) for all 5 Tier-2 missions (SWOT, HyspIRI, ASCENDS, ACE, Geo-CAPE); early pre-formulation studies are funded at ~$1-2 million/year for each mission in FY2010. (p. 6)	NASA has NOT manifested a GPS receiver on every LEO mission. (p. 10)

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
Recommendation: **U.S. civil space agencies should aggressively pursue technology development that supports the missions recommended in Tables ES.1 and ES.2; plan for transitions to continue demonstrably useful research observations on a sustained, or operational, basis; and foster innovative space-based concepts. In particular:** (p. 12)		
• **NASA should increase investment in both mission-focused and cross-cutting technology development to decrease technical risk in the recommended missions and promote cost reduction across multiple missions. Early technology-focused investments through extended mission Phase A studies are essential.** (p. 12)	NASA's competitive Earth Science Technology Office's program has been focused on the needs of the 15 identified NASA decadal survey missions since ROSES 2008. AT PRESENT (not counting previous ESTO projects), NASA is funding over twenty investments in technology development that support the Tier 2 survey missions. These include advanced remote sensing instrument developments such as lidars to measure carbon dioxide, thermal spectrometers to measure minerals and water resources, an interferometric synthetic aperture radar to measure ocean topography, a radiometer to measure carbon monoxide, a Fourier transform spectrometer to measure trace gases, a polarimetric aerosol imager, a cloud profiling radar, and an ocean color radiometer. There are also many component technologies funded, such as lightweight, deployable telescopes and antennas, optical receivers and detectors, and radio frequency receivers. A portion of the FY2009 ARRA/Stimulus funding for ESD was specifically set aside to augment support for competitively selected Earth Science Technology projects. Specific investments by mission are shown in Table 1. (p. 6)	NASA's competitive Earth Science Technology Office's program has been focused on the 15 identified NASA decadal survey missions since ROSES 2008. NASA has funded over 70 new, competitively selected projects that support the survey missions. These include advanced remote sensing instrument developments such as lidars to measure carbon dioxide, thermal spectrometers to measure minerals and water resources, an interferometric synthetic aperture radar to measure ocean topography, a radiometer to measure carbon monoxide, a Fourier transform spectrometer to measure trace gases, a polarimetric aerosol imager, a cloud profiling radar, and an ocean color radiometer. There are also many component technologies funded, such as lightweight, deployable telescopes and antennas, optical receivers and detectors, and radio frequency receivers. A portion of the FY2009 ARRA/Stimulus funding for ESD was specifically set aside to augment support for competitively selected Earth Science Technology projects. Upon publication of the decadal survey in 2007, ESTO investments **already supported all 18 of the recommended mission concepts**. Since then, ESTO has awarded **74** additional technology projects representing an investment of ***over $172 million directly related to the Earth science priorities outlined by the decadal survey.*** (pp. 14-15)

continues

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
• **To restore more frequent launch opportunities and to facilitate the demonstration of innovative ideas and higher-risk technologies, NASA should create a new Venture class of low-cost research and application missions (~$100 million to $200 million). These missions should focus on fostering revolutionary innovation and on training future leaders of space-based Earth science and applications.** (p. 12)	A Venture-class line for regularly selected, competitively selected, PI-led, science-driven, cost- and schedule-constrained investigations has been established within the Earth System Science Pathfinder program. The first solicitation, for airborne studies (up to 4 complete investigations expected to be selected, each up to $30 million) was released on 10 July 2009, with selections and funding expected in Q1 of CY2010. [Biennial] solicitations are budgeted and expected, alternating between orbital and suborbital (airborne) investigations. The next solicitation, expected to be released in summer 2011, will call for instruments to fly on spaceborne Missions of Opportunity (up to 2 proposals expected to be selected, in the $80 million to $100 million class). (pp. 7-8)	A "3-strand" Venture-class line for regularly selected, competitively selected, PI-led, science-driven, cost- and schedule-constrained investigations has been established. (p. 43) (See pp. 17-19 of Freilich's presentation for more on Earth Venture)
• **NOAA should increase investment in identifying and facilitating the transition of demonstrably useful research observations to operational use.** (p. 12)	This is a recommendation to NOAA. NOAA has identified NOAA scientific and engineering points-of-contact for each new NASA decadal survey mission. The president's FY2010 budget request for the Department of Commerce includes NOAA funding to initiate development of Jason-3 in partnership with EUMETSAT and ESA. As noted above, NOAA is actively negotiating with JAXA for provision of a scatterometer for flight on GCOM-W2. (p. 8)	This is a recommendation to NOAA. NOAA has identified NOAA scientific and engineering POCs for each new NASA decadal survey mission. Starting in FY2011, NOAA received funding to initiate development of Jason-3 in partnership with EUMETSAT, with CNES and NASA as junior partners. Until passage of the FY2011 Full-year CR, NOAA was actively negotiating with JAXA for provision of a scatterometer for flight on GCOM-W2 (with NASA technical support); however, this is no longer being pursued by NOAA (although being considered to be taken up by NASA). (p. 43)
The committee endorses the recommendation of a 2006 National Research Council report that stated, "NASA/SMD [Science Mission Directorate] should develop a science strategy for obtaining long-term, continuous, stable observations of the Earth system that are distinct from observations to meet requirements by NOAA in support of numerical weather prediction." (p. 13)	Technical challenges, Congressional interest and directed scope changes (e.g., addition of thermal infrared capability to LDCM, refurbishment of the Earth observing instruments on DSCOVR, mandated NASA co-funding with NOAA of future scatterometer mission studies), international/interagency partner challenges (e.g., Aquarius and NPP), and budgetary limitations constrain ESD to focus on development and expeditious launch of the 5 Foundational missions (Glory, Aquarius, NPP, LDCM, GPM), initiation of the Tier-1 decadal survey missions (SMAP, ICESAT-2, CLARREO, and DESDynI), and science/technology studies for Tier-2 and Tier-3 decadal survey missions. (p. 8)	With the release of the President's FY2011 Budget Request, NASA was given the explicit mandate to examine possible climate continuity missions and include them in the Climate Initiative submitted by NASA ESD to OSTP, USGCRP, and OMB. SAGE-III (2015), OCO-3 (2015), GRACE-FO (2016), and PACE (2019-2020) were identified and included as Climate Continuity Missions. (p. 20)

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
Recommendation: **The Office of Science and Technology Policy, in collaboration with the relevant agencies and in consultation with the scientific community, should develop and implement a plan for achieving and sustaining global Earth observations. This plan should recognize the complexity of differing agency roles, responsibilities, and capabilities as well as the lessons from implementation of the Landsat, EOS, and NPOESS programs.** (p. 14)	This is a recommendation to OSTP. NASA has been an active collaborator in discussions and analyses of NPOESS restructuring scenarios. NASA ESD has provided briefs to OSTP and OMB, and stands ready to support the Administration in its efforts to implement cross-agency coordination mechanisms to develop and operate an efficient, predictable, high-quality, spaceborne environmental observing system for sustained measurements in support of short-term predictions, research, and climate science. (p. 8)	**This is a recommendation to OSTP.** NASA was an active collaborator in discussions and analyses of NPOESS restructuring scenarios; NASA/JASD implements JPSS, Climate Sensors, Jason-3 (to transfer) for NOAA, and Landsat-9 (to come) for USGS. NASA ESD provides leadership (Freilich Vice-Chair 2010-, Kaye acting head 2009-2010) to USGCRP; NASA ESD provides 49% of the total USGCRP distributed cost budget. (p. 21)
Recommendation: **Earth system observations should be accompanied by a complementary system of observations of human activities and their effects on Earth.** (p. 14)	No additional actions taken at this time. NASA continues to fund the Socioeconomic Data and Applications Center (SEDAC) operated by the Center for International Earth Science Information Network (CIESIN), a unit of the Earth Institute at Columbia University based at Lamont-Doherty Earth Observatory in Palisades, New York. SEDAC's missions are to synthesize Earth science and socioeconomic data and information in ways useful to a wide range of decision makers and other applied users, and to provide an "Information Gateway" between the socioeconomic and Earth science data and information domains. (p. 9)	No additional actions taken at this time. NASA continues to fund the Socioeconomic Data and Applications Center (SEDAC) operated by the Center for International Earth Science Information Network (CIESIN), a unit of the Earth Institute at Columbia University based at Lamont-Doherty Earth Observatory in Palisades, New York. SEDAC's missions are to synthesize Earth science and socioeconomic data and information in ways useful to a wide range of decision makers and other applied users, and to provide an "Information Gateway" between the socioeconomic and Earth science data and information domains. NASA continues to fund the Land Cover/Land Use Change (LCLUC) program of competitively selected investigations to understand the consequences of land cover/land use change on the Ecosystem, using remotely sensed data. (p. 22)
Recommendation: **Socioeconomic factors should be considered in the planning and implementation of Earth observation missions and in developing an Earth knowledge and information system.** (p. 14)	In addition to holding open community workshops in the early stages of mission conceptualization, socioeconomic and related information and needs are provided throughout mission development by active representatives of the Earth Science Division's Applied Science Program. For the decadal survey missions, an Applied Sciences Program point-of-contact has been assigned to each mission to ensure two-way communications between the user and developer communities at all stages, including from the start of mission formulation. (p. 9)	In addition to holding open community workshops in the early stages of mission conceptualization and applications-focused workshops later in mission development life, socioeconomic and related information and needs are provided throughout mission development by active representatives of the Earth Science Division Applied Science Program. For the decadal survey missions, an Applied Sciences HQ POC has been assigned to each mission to ensure two-way communications between the user and developer communities at all stages, including from the start of mission formulation. (p. 23)

continues

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
***Recommendation:* Critical surface-based (land and ocean) and upper-air atmospheric sounding networks should be sustained and enhanced as necessary to satisfy climate and other Earth science needs in addition to weather forecasting and prediction.** (p. 14)	NASA/ESD continues to sustain and expand ground-based observation networks, such as AERONET, SLR, VLBI, and GNSS. All of the latter are topics of focused working groups instituted by NASA with the Chinese National Space Agency; similarly, new international agreements are continuously sought and approved in all in-situ network areas to expand the geographical coverage of networks and increase their quality. In conjunction with planned OCO and GOSAT validations, NASA has added 3 sites to the international TCCON network of ground-based calibrated Fourier Transform Spectrometers. (p. 9)	NASA/ESD continues to sustain and expand ground-based observation networks, such as Aeronet, SLR, VLBI, and GNSS. New international agreements are continuously sought and approved in all in-situ network areas to expand the geographical coverage of networks and increase their quality. In conjunction with planned OCO-2 and ongoing GOSAT validations, NASA added 3 sites to the international TCCON network of ground-based calibrated Fourier Transform Spectrometers. An update of the Geodetic Network was included specifically as part of the Climate Initiative. (p. 24)
***Recommendation*: To facilitate the synthesis of scientific data and discovery into coherent and timely information for end users, NASA should support Earth science research via suborbital platforms: airborne programs, which have suffered substantial diminution, should be restored, and unmanned aerial vehicle technology should be increasingly factored into the nation's strategic plan for Earth science.** (p. 14)	ESD has expanded the airborne program in many ways over the last 3 years, and continues to revitalize and expand the capabilities in close collaboration with the research and applications communities. Significant additional resources have been added to the airborne science program to cover maintenance and routine operations of the airborne fleet (routine activities which in many cases had to be funded directly from the research science budget). A majority of the airborne science fleet has been collocated at Site 9 in Palmdale, facilitating access to the airborne platforms by non-NASA (and non-citizen) students and researchers. Formal coordination and associated documentation have resulted in more standard, more straightforward interface definitions/requirements for contributed instruments, allowing easier and platform-independent transfers and integrations. Coordination with the FAA has allowed much-expanded use of UAS platforms in the national airspace, contributing to the now-routine use of NASA UAS and instrumentation in support of wildfire containment efforts on both coasts. In a joint effort between NASA and Northrop Grumman, 2 Global Hawk (Predator) UASs have been added to the research fleet, vastly expanding the long-duration, heavy-lift, high-altitude capabilities available to NASA researchers.	ESD has expanded the airborne program over the last 3 years, and continues to revitalize and expand the capabilities in close collaboration with the research and applications communities. Significant resources have been added to the airborne science program to cover maintenance and routine operations of the airborne fleet (previously funded directly from the research science budget). Formal coordination and associated documentation have resulted in more standard, more straightforward interface definitions/requirements for contributed instruments, allowing easier and platform-independent transfers and integrations. Coordination with the FAA has allowed expanded use of UAS platforms in the national airspace, contributing to the now-routine use of NASA UAS and instrumentation in support of wildfire containment efforts on both coasts. In a joint effort between NASA and Northrop Grumman, 2 Global Hawk (Predator) UASs have been added to the research fleet, vastly expanding the long-duration, heavy-lift, high-altitude capabilities available to NASA researchers. In addition to the airborne Venture-class solicitation discussed above, ESD has supported twice-yearly ICE Bridge airborne campaigns in both the Arctic and Antarctic to span the gap between the demise of ICESAT-1 and the launch of ICESAT-2. (p. 25)

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
	In addition to the airborne Venture-class solicitation discussed above, ESD has begun twice-yearly ICE Bridge airborne campaigns in both the Arctic and Antarctic to span the gap between the expected demise of ICESAT-1 and the launch of ICESAT-2. Airborne science flight hours increased more than 60% in 2008 over 2007, with additional increases on track this year. (p. 10)	
Recommendations:		
• **Teams of experts should be formed to consider assimilation of data from multiple sensors and all sources, including commercial providers and international partners.** (p. 15)	NASA continues to support and fund multiagency, multi-institution assimilation efforts including the Joint Center for Satellite Data Assimilation (JCSDA), the Short-Term Prediction and Research Transition Center (SPoRT) to transition unique observations and research capabilities to the operational weather community to improve short-term forecasts on a regional scale, the massive MERRA (Modern Era Retrospective-Analysis for Research and Applications) reanalysis project at the Global Modeling and Assimilation Office (GMAO), and a variety of similar assimilation and modeling activities in association with international initiatives such as GODAE (Global Ocean Data Assimilation Office). NASA is preparing for a major role in the upcoming IPCC Fifth Assessment Report modeling and analysis effort. (p. 10)	NASA continues to support and fund multiagency, multi-institution assimilation efforts including the Joint Center for Satellite Data Assimilation (JCSDA), the Short-Term Prediction and Research Transition Center (SPoRT) to transition unique observations and research capabilities to the operational weather community to improve short-term forecasts on a regional scale, the MERRA (Modern Era Retrospective-Analysis for Research and Applications) reanalysis project at the Global Modeling and Assimilation Office (GMAO), and a variety of similar assimilation and modeling activities in association with international initiatives such as GODAE (Global Ocean Data Assimilation Office). NASA is preparing for a major role in the upcoming IPCC Fifth Assessment Report modeling and analysis effort. (p. 30)
• **NOAA, working with the Climate Change Science Program and the international Group on Earth Observations, should 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.** (p. 15)	This is a recommendation to NOAA. (p. 10)	This is a recommendation to NOAA. (p. 30)

continues

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
• **As new Earth observation missions are developed, early attention should be given to developing the requisite data processing and distribution system, and data archive. Distribution of data should be free or at low cost to users, and provided in an easily accessible manner.** (p. 15)	Data processing, archive, and distribution activities are budgeted fully from the start in all NASA flight missions, specifically including the identified decadal survey missions. Approximately 11% of the entire ESD annual budget is focused specifically on multi-mission operations (EOSDIS and related information systems) activities. NASA continues to maintain a free and open distribution policy for all mission data, with no period of priority. (p. 11)	Data processing, archive, and distribution activities are budgeted fully from the start in all decadal survey missions. Approximately 9% of the entire ESD annual budget is focused specifically on multi-mission operations (EOSDIS and related information systems) activities. NASA continues to maintain a free and open distribution policy for all mission data, with no period of priority. (p. 31)
• **NASA should increase support for its research and analysis (R&A) program to a level commensurate with its ongoing and planned missions. Further, in light of the need for a healthy R&A program that is not mission-specific, as well as the need for mission-specific R&A, NASA's space-based missions should have adequate R&A lines within each mission budget as well as mission-specific operations and data analysis. These R&A lines should be protected within the missions and not used simply as mission reserves to cover cost growth on the hardware side.** (p. 15)	ESD continues to fund vigorous, competitively selected R&A and Applied Sciences programs to advance Earth System science, develop applications, synthesize and combine measurements from multiple spaceborne missions as well as in situ observations, and to identify the next generation of tractable, important Earth science problems that are amenable to spaceborne data acquisition. Accounting for just under half of the total ESD budget, these research and related supporting activities (such as data systems) include science budgets for mission science teams as well as the R&A portion of the budget structure. Mission science team lines are monitored by HQ Program Scientists and are "fenced" to protect them from technical challenges and associated cost increases during mission development. (p. 11)	ESD continues to fund competitively selected R&A and Applied Sciences programs to advance Earth System science; develop applications, synthesize and combine measurements from multiple spaceborne missions as well as in situ observations, and to identify the next generation of tractable, important Earth science problems that are amenable to spaceborne data acquisition. Accounting for just under half of the total ESD budget, these research and related supporting activities (such as data systems) include science budgets for mission science teams as well as the R&A portion of the budget structure. Mission science team lines are monitored by HQ Program Scientists and are protected from technical challenges and associated cost increases during mission development. (p. 32)
• **NASA, NOAA, and USGS should increase their support for Earth system modeling, including provision of high-performance computing facilities and support for scientists working in the areas of modeling and data assimilation.** (p. 15)	In addition to the assimilation-related activities discussed above, a portion of the ARRA/Stimulus funding has been set aside for modeling-specific work. ROSES 2008 included a major solicitation for the Modeling, Analysis, and Prediction (MAP) activity that supports observation driven modeling that integrates the research activities within the R&A element. In addition to community grants, the MAP element supports basic modeling infrastructure as well as research activities at Goddard Institute for Space Studies, the NASA Goddard Global Modeling and Assimilation Office, and the Global Modeling Initiative (Chemical Transport Modeling)	In addition to the assimilation-related activities discussed above, a portion of the Stimulus funding has been set aside for modeling-specific work. ROSES 2008 included a major solicitation for the Modeling, Analysis, and Prediction activity that supports observation driven modeling that integrates the research activities within the R&A element. In addition to community grants, the MAP element supports basic modeling infrastructure as well as research activities at GISS, GMAO, and the Global Modeling Initiative (Chemical Transport Modeling).

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
	Specific foci of the solicitation included Integrated studies of weather and climate emphasizing the role of weather in the climate system through the use of multiparameter observations from satellites to evaluate and characterize (i.e., validate) model simulations, coupled model investigations designed to examine the representation of Earth system processes spanning a continuum of time and space scales associated with weather and climate, development of climate information from numerical simulations that can be applied at spatial and temporal scales suitable for increasing society's resilience to climate change and development of climate change adaptation strategies, development of innovative ways to apply Observation System Simulation Experiments to climate prediction and the future design of space-based observing systems, investigations using the Modern Era Retrospective- analysis for Research and Applications (MERRA) reanalysis data, Ice Sheet Modeling to incorporate ice streams into the interior ice sheet with particular emphasis on the Greenland outflow glaciers and their coupling with the interior, Atmospheric Chemistry Hindcast investigations forcing Chemistry and Transport Models (CTMs) with multiyear meteorological fields derived from global reanalysis systems, and Advanced Model Dynamics and Numerics investigations of grids and fluid dynamical formulations that support high resolution simulation of the Earth's climate. The call resulted in 52 investigations being selected, most for a period of 4 years. (p. 12)	The solicitation included Integrated studies of weather and climate emphasizing the role of weather in the climate system through the use of multiparameter observations from satellites to evaluate and characterize (i.e., validate) model simulations, coupled model investigations designed to examine the representation of Earth system processes spanning a continuum of time and space scales associated with weather and climate, development of climate information from numerical simulations that can be applied at spatial and temporal scales suitable for increasing society's resilience to climate change and development of climate change adaptation strategies, development of innovative ways to apply Observation System Simulation Experiments to climate prediction and the future design of space-based observing systems, investigations using the Modern Era Retrospective-analysis for Research and Applications (MERRA) reanalysis data, Ice Sheet Modeling to incorporate ice streams into the interior ice sheet with particular emphasis on the Greenland outflow glaciers and their coupling with the interior, Atmospheric Chemistry Hindcast investigations forcing Chemistry and Transport Models (CTMs) with multiyear meteorological fields derived from global reanalysis systems, and Advanced Model Dynamics and Numerics investigations of grids and fluid dynamical formulations that support high resolution simulation of the Earth's climate. The call resulted in 52 investigations being selected, most for a period of 4 years. (pp. 34-35)
Recommendation: **A formal interagency planning and review process should be put into place that focuses on effectively implementing the recommendations made in the present decadal survey report and sustaining and building an Earth knowledge and information system for the next decade and beyond.** (p. 15)	No formal, comprehensive interagency process focused on the decadal survey has been put into place. Details of ongoing relevant activities are discussed at the regular (quarterly) NASA-NOAA Roundtable meetings co-chaired by ESD and NESDIS. (p. 12)	No formal, comprehensive interagency process focused on the decadal survey has been put into place. Details of ongoing relevant activities are discussed at the regular (quarterly) NASA-NOAA Roundtable/Joint Working Group meetings co-chaired by ESD and NESDIS. ESD, JASD, and USGS hold similar periodic bilateral coordination meetings (~3/year). (p. 36)

continues

TABLE E.1 Continued

Decadal Survey Recommendation	NASA's Response (2009)[a]	NASA Update (2011)[b]
***Recommendation:* NASA, NOAA, and USGS should pursue innovative approaches to educate and train scientists and users of Earth observations and applications. A particularly important role is to assist educators in inspiring and training students in the use of Earth observations and the information derived from them.** (p. 15)	ESD continues to support a vigorous Education and Public Outreach program, including annual competitive solicitations for Earth System Science Fellowships, a New Investigator Program, and the GLOBE program. These activities complement other NASA-wide educational activities at the Directorate and Agency levels, with which ESD coordinates closely. The schedule-constrained Venture-Class program described above specifically enables training opportunities for students and post-doctoral researchers and the development and test of cutting-edge, innovative measurement and analysis techniques. (p. 13)	ESD continues to support a vigorous Education and Public Outreach program, including annual competitive solicitations for Earth System Science Fellowships, a New Investigator Program, and the GLOBE program. These activities complement other NASA-wide educational activities at the Directorate and Agency levels, with which ESD coordinates closely. The schedule-constrained Venture-Class program described above specifically enables training opportunities for students and post-doctoral researchers and the development and test of cutting-edge, innovative measurement and analysis techniques. (p. 37)

NOTE: Tables and figures referred to are not reprinted here.

[a]Edward J. Weiler, Associate Administrator, NASA Science Mission Directorate, letter to Charles F. Kennel, Chair, Space Studies Board, National Research Council, dated October 25, 2009.

[b]Michael Freilich, Director, NASA Earth Science Division, "Earth Science Division Decadal Survey Status," presentation to the Committee on the Assessment of NASA's Earth Science Program, April 27, 2011.

F

Committee and Staff Biographical Information

DENNIS L. HARTMANN, *Chair,* is a professor in the Department of Atmospheric Sciences at the University of Washington, where he served as chair and as interim dean of the College of the Environment. He is also the chair of the board of trustees of the University Corporation for Atmospheric Research (UCAR). His main research interests are in low-frequency variability in the atmosphere and climate system, stratospheric ozone, global climate change, large-scale dynamics, and the radiative energy balance of Earth. His primary areas of expertise are atmospheric dynamics, radiation and remote sensing, and mathematical and statistical techniques for data analysis. Dr. Hartmann is a fellow of the American Meteorological Society (AMS), the American Geophysical Union (AGU), the American Association for the Advancement of Science (AAAS), and the Joint Institute for the Study of the Atmosphere and Ocean. He is a recipient of the NASA Distinguished Service Medal. He received his B.S. in mechanical engineering from the University of Portland and a Ph.D. in geophysical fluid dynamics from Princeton University. Dr. Hartmann previously served on the National Research Council (NRC) Board on Atmospheric Sciences and Climate, the Committee on Scientific Accomplishments of Earth Observations from Space, and the Committee for Review of the U.S. Climate Change Science Program's Synthesis and Assessment Product on Temperature Trends in the Lower Atmosphere.

MARK R. ABBOTT is dean of the College of Earth, Ocean, and Atmospheric Sciences, Oregon State University at Corvallis. His research focuses on the interaction of biological and physical processes in the upper ocean, remote sensing of ocean color and sea surface temperature, phytoplankton fluorescence, and length and time scales of phytoplankton variability. He deployed the first array of bio-optical moorings in the Southern Ocean as part of the U.S. Joint Global Ocean Flux Study (JGOFS). Dr. Abbott has chaired the U.S. JGOFS Science Steering Committee and was a member of the MODIS and SeaWiFS science teams. He is currently a member of the board of trustees for the Consortium for Ocean Leadership and a member of the National Science Board. Dr. Abbott was also a member of the NRC's Space Studies Board and chaired its Committee on Earth Studies. Other prior NRC experience includes serving on the Committee on Indicators for Understanding Global Climate Change, the Committee on the Role and Scope of Mission-Enabling

Activities in NASA's Space and Earth Sciences Missions, and the Panel on Land-Use Change, Ecosystem Dynamics, and Biodiversity for the 2007 decadal survey on Earth science and applications from space.

RICHARD A. ANTHES is president emeritus of the University Corporation for Atmospheric Research (UCAR) in 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, receiving the AMS Clarence I. Meisinger Award and the Jule G. Charney Award and also serving as president of the AMS in 2007. Dr Anthes is a fellow of the AGU, as well. In 2003, he was awarded the Friendship Award by the Chinese government, the most prestigious award given to foreigners, for his contributions to atmospheric sciences and weather forecasting in China, and is also currently a member of the Global Positioning System (GPS) Scientific Application Research Center based out of Taiwan's National Central University. Dr. Anthes received a B.S., M.S., and Ph.D. in meteorology from the University of Wisconsin, Madison. Prior 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, and co-chairing the committee for the 2007 decadal survey on Earth science and applications from space. He was a member of the Space Studies Board's Committee on Earth Studies until 2010.

PHILIP E. ARDANUY is a principal engineering fellow at Raytheon Intelligence and Information Systems and serves as chief technologist and chief scientist on multiple NASA, National Oceanic and Atmospheric Administration (NOAA), and Environmental Protection Agency projects. He specializes in developing integrated mission concepts through government-industry-academic partnerships. His research and development career extends across net-centric and system-of-systems concepts; remote sensing applications and systems engineering; the research-to-operational transition; telepresence-telescience-telerobotics; tropical meteorology and modeling; Earth's radiation budget (ERB) and climate (as member of the Nimbus-7 ERB science team); satellite instrument calibration, characterization, and validation; science, technology, engineering, and mathematics education; and public outreach. Dr. Ardanuy's prior NRC service includes membership on the Committee on Earth Studies; the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft; the Committee on Environmental Satellite Data Utilization; and the Panel on Earth Science Applications and Societal Benefits for the 2007 decadal survey of Earth science and applications from space. Dr. Ardanuy received his doctorate in meteorology from Florida State University. He has served on the NOAA Science Advisory Board's Environmental Information Services Working Group, UCAR's Weather Coalition, SPIE's Remote Sensing System Engineering Conference as co-chair, and NOAA's CREST Institute External Advisory Board. He is a member of the board of directors and president emeritus of the Maryland Space Business Roundtable, and he currently chairs the AMS Satellite Meteorology, Oceanography, and Climatology committee. Dr. Ardanuy is a fellow of the AMS, and he has been the recipient of multiple NASA group achievement awards, the Raytheon Excellence in Business Development Award, and the Raytheon Peer Award. He has more than 100 publications to his name, including articles in peer-reviewed journals, book chapters, and conference presentations.

STACEY W. BOLAND is a senior systems engineer at the Jet Propulsion Laboratory and is the Observatory System Engineer for the Orbiting Carbon Observatory-2 (OCO-2) Earth System Science Pathfinder mission. She is also a cross-disciplinary generalist specializing in Earth-mission concept development and systems engineering and mission architecture development for advanced (future) Earth observing mission concepts. Dr. Boland received her B.S. in physics from the University of Texas at Dallas, and her M.S. and Ph.D. in mechanical engineering from California Institute of Technology. Dr. Boland was awarded NASA's Exceptional Achievement Medal in 2009. She has served as a consultant to the NRC Earth Science and Applications from Space: A Community Assessment and Strategy for the Future Committee; the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft; and Committee on a Strategy to Mitigate the Impact of Sensor Descopes and Demanifests on the NPOESS and GOES-R Spacecraft. Dr. Boland recently completed membership on the NRC Committee on Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions.

ANTONIO J. BUSALACCHI, JR., is director of the Earth System Science Interdisciplinary Center and a professor in the Department of Atmospheric and Oceanic Science at the University of Maryland. His research interests include tropical ocean circulation and its role in the coupled climate system and climate variability and predictability. Dr. Busalacchi has been involved in the activities of the World Climate Research Program (WCRP) for many years and currently is chair of the Joint Scientific Committee that oversees the WCRP. He previously was co-chair of the scientific steering group for its subprogram on climate variability and predictability. Dr. Busalacchi received a B.S. in physics from Florida State University, and an M.S. and a Ph.D. in oceanography from Florida State University. He has served extensively on NRC activities, including as chair of the Climate Research Committee and Committee on a Strategy to Mitigate the Impact of Sensor Descopes and Demanifests on the National Polar-orbiting Operational Environmental Satellite System and Geostationary Operational Environmental Satellite Spacecraft, and as a member of the Committee on Earth Studies, the Panel on the Tropical Ocean Global Atmosphere Program, and the Panel on Ocean Atmosphere Observations Supporting Short-Term Climate Predictions. Dr. Busalacchi currently serves as chair of the NRC's Board on Atmospheric Sciences, and is co-chair of the Committee on National Security Implications of Climate Change on U.S. Naval Forces, and recently completed service on the Committee on Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions, and the Committee on the Effect of Climate Change on Indoor Air Quality and Public Health.

ANNY CAZENAVE is a senior scientist at the Centre National d'Études Spatiales (CNES) and deputy director of the Laboratory for Space Studies in Geophysics and Oceanography. Dr. Cazenave's major areas of research focus on the application of satellite geodesy to climate change, sea level variation, and large-scale continental hydrology. She is a member of the Global Geodetic Observing System scientific panel and lead author on IPCC Working Group I for Ocean Climate and Sea-level. She is past president of the Geodesy Section of the European Geophysical Union (EGU) and was its Vening-Meinesz Medalist in 1999. She is a member of the National Academy of Sciences, the French Academy of Sciences, the Academia Europaea, the the Académie de l'Air et de l'Espace, and she is a fellow of the AGU. Her honors include Officier de l'Ordre National du Mérite and Chevalier de la Légion d'Honneur and election to the National Academy of Sciences. Dr. Cazenave received her Ph.D. in geophysics from the University of Toulouse. Prior NRC service includes membership on the Committee on National Requirements for Precision Geodetic Infrastructure, the Panel on Water Resources and the Global Hydrologic Cycle for the 2007 decadal survey on Earth science and applications from space, and the Committee to Review NASA's Solid Earth Science Strategy.

RUTH S. DeFRIES is the Denning Professor of Sustainable Development at Columbia University. Before joining Columbia University, Dr. DeFries was a professor at the University of Maryland, where she held joint appointments in the Department of Geography and the Earth System Science Interdisciplinary Center. Her research investigates the relationships between human activities, the land surface, and the biophysical and biogeochemical processes that regulate Earth's habitability. She is interested in observing land-cover and land-use change on regional and global scales with remotely sensed data and exploring the implications for ecological services, such as climate regulation, the carbon cycle, and biodiversity. Dr. DeFries received a B.A. in earth science from Washington University in St. Louis, and a Ph.D. in geography and environmental engineering from Johns Hopkins University. She is a member of the National Academy of Sciences and a fellow of the AGU and the AAAS. Prior NRC experience includes serving as a chair of the NRC Committee on Earth System Science for Decisions about Human Welfare: Contributions of Remote Sensing, as a member of the Geographical Sciences Committee, and as a member of the survey committee for the 2007 decadal survey on Earth science and applications from space. She is currently a member of the Proceedings of the National Academies of Sciences Editorial Board, and the NRC Committee on Climate, Energy, and National Security.

LEE-LUENG FU is a JPL fellow and a senior research scientist at the Jet Propulsion Laboratory, California Institute of Technology. He has been the project scientist for JPL's satellite altimetry missions since 1988, including TOPEX/Poseidon, Jason, and Ocean Surface Topography Mission/Jason-2. He is currently the project scientist for the U.S./France joint Surface Water and Ocean Topography Mission (SWOT), which is being developed as the next-generation altimetry mission for measuring water elevation on Earth. Dr. Fu's research has been focused on the dynamics of ocean waves and currents ranging from small-scale internal gravity waves to ocean basin-scale circulation. He received a B.S. degree in physics from National Taiwan University (1972) and a Ph.D. in oceanography from Massachusetts Institute of Technology and Woods Hole Oceanographic Institution (1980). He is a member of the U.S. National Academy of Engineering, and a fellow of the American Geophysical Union and the American Meteorological Society. Recently he was awarded the COSPAR International Cooperation Medal for his leadership in the development and continuation of satellite altimetry missions.

BRADFORD H. HAGER is the Cecil and Ida Green Professor of Earth Sciences in the Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology (MIT). Dr. Hager is an expert in using precise measurements of ground deformation derived from GPS (Global Positioning System) observations and laser ranging, as well as interferometric synthetic aperture radar measurements to study earthquakes, seismic hazards, hydrocarbon reservoir mechanics, and underground CO_2 storage. While teaching at the California Institute of Technology, Dr. Hager began the GPS field experiment that led to the discovery of rapid strain accumulation in the epicentral region of the 1994 Northridge Earthquake. He has been involved in other similar field projects around the world, including in the Tien Shan Mountains of central Asia and the Southern Alps in New Zealand. Dr. Hager was co-chair of NASA's DESDynI Science Study Group, a satellite mission to measure deformation of the land surface and ice sheets, as well as changes in terrestrial biomass. He is a fellow of the American Geophysical Union and a recipient of AGU's Macelwane Medal, as well as a fellow of the American Academy of Arts and Sciences and a recipient of the Geological Society of America's Woolard Award and the European Geophysical Union's Love Medal. Dr. Hager received a B.A. in physics from Amherst College, an M.A. in geology from Harvard University, and his Ph.D. in geophysics from Harvard University. He has previously served on the NRC Steering Committee for Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, the Panel on Solid-Earth Hazards, Resources and Dynamics, the Committee to Review NASA's Solid Earth Science Strategy, and the Committee for Review of the Science Implementation Plan of the NASA Office of Earth Science.

HUNG-LUNG (ALLEN) HUANG is a Distinguished Scientist of the University of Wisconsin, Madison, and a senior research scientist at the university's Cooperative Institute for Meteorological Satellites Studies (CIMSS), which operates as an institute within the Space Science Engineering Center (SSEC). While at CIMSS/SSEC, Dr. Huang has been conducting remote sensing research in the areas of atmospheric sounding retrieval, information content analysis, satellite and aircraft high-spectral resolution sounding instrument data processing, data compression, instrument design and performance analysis, cloud-clearing, cloud property characterization, synergistic imaging, and sounding data processing and algorithm development. Dr. Huang is also principal investigator of the NASA-funded International Moderate Resolution Imaging Spectroradiometer/Atmospheric Infrared Sounder Instrument Processing project, the NOAA Integrated Program Office International Polar Orbiter Processing Package, and the NASA Field Programmable Gate Array Re-Configurable Computation Demonstration project, and he is the program manager and lead scientist of algorithm development for the NOAA Geostationary Operational Environmental Satellite (GOES)-R risk reduction project. He is a member of the International Society for Optical Engineering (SPIE), the AMS, the Optical Society of America, and the International Radiation Commission. Dr. Huang received a B.S. in atmospheric science from National Taiwan University and an M.S. and a Ph.D. in meteorology from the University of Wisconsin, Madison. For the NRC, he served as chair of the Committee on Utilization of Environmental Satellite Data: A Vision for 2010 and Beyond and as a member of the Committee on Earth Studies.

ANTHONY C. JANETOS is director of the Joint Global Change Research Institute, part of the Pacific Northwest National Laboratory, with research-affiliate status at the University of Maryland. Earlier, he was a senior research fellow at the H. John Heinz III Center for Science, Economics, and the Environment. In 1999, he joined the World Resources Institute as senior vice president and chief of programs. Previously, he served as senior scientist for the Land-Cover and Land-Use Change Program in NASA's Office of Earth Science and was program scientist for the Landsat 7 mission. He had many years of experience in managing scientific research programs on a variety of ecologic and environmental topics, including air-pollution effects on forests, climate change impacts, land-use change, ecosystem modeling, and the global carbon cycle. Dr. Janetos received his B.S. in biology from Harvard University, and his M.S. and Ph.D. in biology from Princeton University. He was a co-chair of the U.S. National Assessment of the Potential Consequences of Climate Variability and Change and an author of *Land-Use, Land-Use Change, and Forestry* (an IPCC special report) and *Global Biodiversity Assessment*. Prior NRC experience includes serving on the survey committee for the 2007 decadal survey on Earth science and applications from space, the Committee on Ecological Impacts of Climate Change, and the Climate Research Committee. Dr. Janetos is currently a member of the Committee on Socioeconomic Scenarios for Climate Change Impact and Response Assessments, and of the Space Studies Board.

DENNIS P. LETTENMAIER is the Robert and Irene Sylvester Professor of Civil and Environmental Engineering and the head 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 the American Society of Civil Engineers' Huber Research Prize in 1990, is a fellow of the AGU, AAAS, and the AMS, and is the author of more than 200 journal articles. He was the founding chief editor of the AMS *Journal of Hydrometeorology* and the president of the AGU Hydrology Section. He is a member of the International Water Academy and the National Academy of Engineering. Dr. Lettenmaier received a B.S. in mechanical engineering from the University of Washington, an M.S. in civil, mechanical, and environmental engineering from the George Washington University, and a Ph.D. in civil engineering from the University of Washington. He has previously served as a member on numerous NRC committees, including the Committee on Hydrologic Science: Studies of Strategic Issues in Hydrology, the survey committee for the 2007 decadal survey on Earth science and applications from space, and most recently the Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations.

JENNIFER A. LOGAN is a senior research fellow in the School of Engineering and Applied Sciences at Harvard University. Dr. Logan's research focuses on analysis of satellite and in situ observations of tropospheric composition and their use in evaluation of processes in chemical transport models; causes of interannual variability and trends in tropospheric composition; trace gas budgets; the effects of climate change on fires and air quality; and trends in stratospheric ozone. Dr. Logan is a fellow of the AGU and the AAAS. She was a coauthor of the past several Scientific Assessments of Ozone Depletion. She received a B.Sc. in chemistry from the University of Edinburgh and a Ph.D. in physical chemistry from the Massachusetts Institute of Technology. Prior NRC service includes membership on the Committee on the Role and Scope of Mission-Enabling Activities in NASA's Space and Earth Science Mission, the Board on Atmospheric Sciences and Climate, and the Committee to Assess the North American Research Strategy for Tropospheric Ozone (NARSTO) Program.

MOLLY K. MACAULEY is vice president for research and a senior fellow at Resources for the Future (RFF), in Washington, D.C. RFF was established in 1952 upon request of a U.S. presidential commission and serves to advance economics research on environmental and natural resources. Dr. Macauley's research at RFF includes studies on economics and policy issues of outer space, the valuation of non-priced space resources, the design of incentive arrangements to improve space resource use, and the appropriate relationship between public and private endeavors in space research, development, and commercial enterprise. Dr. Macauley serves as a visiting professor in the Department of Economics at Johns Hopkins University. She has frequently testified before Congress and serves on many national-level committees and panels. She serves on the Board of Trustees of the University Corporation for Atmospheric Research, the Board of Directors of the American Astronautical Society, the Board of Advisors of the Thomas Jefferson Public Policy Program at the College of William and Mary, and the Women in Aerospace Scholarship Fund. Dr. Macauley currently serves as a member of the NRC's Space Studies Board. Prior NRC service includes the Aeronautics and Space Engineering Board, the Panel on Earth Science Applications and Societal Needs for the 2007 decadal survey on Earth sciences and applications from space, the Committee on the Assessment of NASA's Orbital Debris Program, and the Science Panel of the Review of NASA Strategic Roadmaps. Her B.A. in economics is from the College of William and Mary and her Ph.D. in economics is from Johns Hopkins University.

ANNE W. NOLIN is a professor of remote sensing and physical geography at Oregon State University (OSU). Prior to her appointment at OSU, Dr. Nolin was a research scientist at the National Snow and Ice Data Center, part of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder. Her research interests include snow hydrology, polar climatology, the martian polar ice caps, and remote sensing of snow and ice from airborne and space-borne sensors. She specializes in mountain hydroclimatology, snow and ice in the climate system, and remote sensing. She is currently a member of the Multiangle Imaging SpectroRadiometer (MISR) Science Team and was a NASA principal investigator for the validation of snow albedo retrievals from MISR and MODIS (Moderate Resolution Imaging Spectroradiometer). She received a B.A. from the University of Arizona in anthropology, an M.S. from the University of Arizona in soil science, and a Ph.D. in physical geography from the University of California at Berkeley. Dr. Nolin served as vice chair of the NRC Panel on Water Resources and the Global Hydrologic Cycle for the study "Earth Science and Applications from Space: A Community Assessment and Strategy for the Future," was a member of the Committee on a Strategy to Mitigate the Impact of Sensor De-scopes and De-manifests on the NPOESS and GOES-R Spacecraft, and was also a member of the Committee on Earth Studies of the Space Studies Board.

JOYCE E. PENNER is the Ralph J. Cicerone Distinguished University Professor of Atmospheric Science and director of the Laboratory for Atmospheric Science and Environmental Research at the University of Michigan. Dr. Penner's research focuses on improving climate models through the addition of interactive chemistry and the description of aerosols and their direct and indirect effects on the radiation balance in climate models. She is also interested in urban, regional, and global tropospheric chemistry and budgets, cloud and aerosol interactions and cloud microphysics, climate and climate change, and model development and interpretation. Dr. Penner has been a member of numerous advisory committees related to atmospheric chemistry, global change, and Earth science, including the United Nations' Intergovernmental Panel on Climate Change (IPCC) and, consequently, she shared in the 2007 Nobel Peace Prize given to the IPCC. She was the coordinating lead author for IPCC (2001) Chapter 5 on aerosols. Dr. Penner received a B.A. in applied mathematics from the University of California, Santa Barbara, and her M.S. and Ph.D. in applied mathematics from Harvard University. She is currently a member of the NRC U.S. National Committee for the International Union of Geodesy and Geophysics. Prior NRC service includes being a member of the Space Studies Board, the planning committee for the Workshop on Uncertainty Management in Remote Sensing of Climate Data, and the Panel on Climate Variability and Change for the 2007 decadal survey on Earth science and applications from space.

MICHAEL J. PRATHER is the Fred Kavli Chair and a professor in the Department of Earth System Science at the University of California, Irvine. His current research focuses on atmospheric chemistry, uncertainties in projecting future composition, and model simulations of satellite observations of global ozone. Dr. Prather's Ph.D. is in astronomy and astrophysics from Yale University, and he has since worked at Harvard University, NASA the Goddard Institute for Space Studies, and NASA Headquarters, and he has taken a year at the U.S. State Department as a Jefferson Science Fellow. Dr. Prather served as editor-in-chief of *Geophysical Research Letters* (1997-2001) during AGU's transition to electronic publishing. He has been lead author on World Meteorological Organization/UNEP ozone assessments since 1985, and IPCC climate assessments since 1994. Dr. Prather has served on numerous NRC committees, including the Committee on Methods for Estimating Greenhouse Gas Emissions, the Panel on Climate Variability and Change of the 2007 decadal survey on Earth science and applications from space, and the Committee for Review of the U.S. Climate Change Science Program Strategic Plan.

DAVID S. SCHIMEL is the chief executive officer of the National Ecological Observatory Network, Inc. He was formerly the senior scientist at the National Center for Atmospheric Research in Colorado, Director of the Max Planck Institut fur Biogeochimie in Jena, Germany, and a senior scientist of the Natural Resources and Ecology Laboratory at Colorado State University. His areas of scientific interest are in biogeochemistry, atmosphere-biosphere exchange, and carbon cycle and climate impacts. Dr. Schimel shared in the Nobel Peace Prize that was awarded in 2007 to the Intergovernmental Panel on Climate Change report, and he is editor in chief of *Ecological Applications* for the Ecological Society of America. He received his Ph.D. in ecology from Colorado State University. Dr. Schimel served on the NRC's Panel on Land-Use Change, Ecosystem Dynamics, and Biodiversity for the 2007 decadal survey on Earth science and applications from space. He also served on the Committee on Geophysical and Environmental Data, among others.

WILLIAM F. TOWNSEND is an independent consultant and a part-time advisor with Stellar Solutions, Inc. He is also co-owner of Townsend Aerospace Consulting, LLC. Previously, Mr. Townsend worked at Ball Aerospace and Technologies Corporation. Mr. Townsend joined Ball in 2004 as the vice president and general manager of the Civil Space Systems Strategic Business Unit; his concluding position in 2008 was vice president of exploration systems. Mr. Townsend had a long career at NASA prior to his appointment at Ball. At Goddard Space Flight Center (GSFC) he was deputy center director and program management council chairperson, where he oversaw the development, launch, and operation of all GSFC instruments, spacecraft, and missions, and was closely involved with almost 60 missions during his NASA career, including more than 30 missions while at GSFC. At NASA Headquarters, in the Earth Science Enterprise area, he held the positions of acting associate administrator, deputy associate administrator, deputy division director, and flight program branch chief and was program manager of the TOPEX/Poseidon, NASA Scatterometer, and Radarsat programs (all international). At the NASA Wallops Flight Center, Mr. Townsend served as the SeaSat Radar Altimeter Experiment manager, an aerospace technologist, and an electronic technician apprentice. He holds a BSEE with honors from Virginia Tech. He is the recipient of two presidential rank, meritorious executive awards, two NASA Distinguished Service Medals, the NASA Outstanding Leadership Medal, the GSFC Robert C. Baumann Memorial Award for Mission Success, the NASA Exceptional Service Medal, and the French Space Agency's Bronze Medal. Mr. Townsend served on the NRC's Committee on Cost Growth in NASA Earth and Space Science Missions.

THOMAS H. VONDER HAAR is the emeritus director of the Cooperative Institute for Research in the Atmosphere (CIRA) and a university distinguished professor of atmospheric science at Colorado State University. His research included work on Earth's radiation budget and fundamental relationships with the climate system and incorporated some of the first results of direct solar irradiance measurements from satellites and the exchange of energy between Earth and space. His studies on the interaction of clouds, water vapor, and radiation and the general circulation formed a basis for national and international plans leading to the Global Energy and Water Experiment and other programs related to global change. In 1980, Dr. Vonder Haar spearheaded the formation of CIRA, a center for international cooperation in research and training, covering virtually all physical, economic, and societal aspects of weather and climate. CIRA was established to increase the effectiveness of atmospheric research in areas of mutual interest between Colorado State and NOAA. Dr. Vonder Haar has also served as director of the Center for Geosciences, a Department of Defense-sponsored research center that focuses on the study of weather patterns and how they affect military operations, including investigations of fog, cloud layering, cloud drift winds, and dynamics of cloud persistence as detected from satellites. Dr. Vonder Haar is a member of the National Academy of Engineering. He received his B.S. in aeronautics from St. Louis University, and his M.S. and Ph.D. in meteorology from the University of Wisconsin at Madison. Dr. Vonder Haar currently serves on the NRC's Special Fields and Interdisciplinary Engineering Peer Committee. Prior NRC service includes serving as a member of the Board on Atmospheric Sciences and Climate, the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft, and the Panel on Weather Science and Applications for the 2007 decadal survey on Earth science and applications from space.

Staff

ARTHUR A. CHARO, *Study Director*, joined the Space Studies Board (SSB) in 1995 as a senior program officer. He has directed studies that have resulted in some 33 reports, notably the first NRC decadal survey in solar and space physics (2003) and in Earth science and applications from space (2007). Dr. Charo 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. He then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a research fellow from 1985 to 1988. From 1988 to 1995, he worked as a senior analyst and study director in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-

Sloan Foundation Fellowship (1987-1988). He was also the 1988-1989 American Institute of Physics AAAS Congressional Science Fellow. In addition to NRC reports, he is the author of research papers in molecular spectroscopy, reports on arms control and space policy, and the monograph "Continental Air Defense: A Neglected Dimension of Strategic Defense" (University Press of America, 1990).

CATHERINE A. GRUBER, editor, joined the 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 also worked as an outreach assistant for the 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.

LEWIS B. GROSWALD, research associate, joined the SSB as the Autumn 2008 Lloyd V. Berkner Space Policy Intern. Mr. Groswald is a graduate of George Washington University, where he received a master's degree in international science and technology policy and a bachelor's degree in international affairs, with a double concentration in conflict and security and Europe and Eurasia. Following his work with the National Space Society during his senior year as an undergraduate, Mr. Groswald decided to pursue a career in space policy, with a focus on educating the public on space issues and formulating policy. He has worked on NRC reports covering a wide range of topics, including near-Earth objects, orbital debris, life and physical sciences in space, and planetary science.

LINDA M. WALKER, a senior project assistant, has been with the NRC since 2007. Before her assignment with the SSB, she was on assignment with the National Academies Press. Prior to working at the NRC, she was with the Association for Healthcare Philanthropy in Falls Church, Virginia. Ms. Walker has 28 years of administrative experience.

DANIELLE PISKORZ, a SSB Lloyd V. Berkner space policy intern, grew up on Long Island, New York, and recently graduated from the Massachusetts Institute of Technology with a degree in physics and a minor in applied international studies. She has done various research projects at L'Institut d'Astrophysique de Paris, Los Alamos National Laboratories, and the Jet Propulsion Laboratory and spent her junior year studying at the University of Cambridge. Ms. Piskorz plans to begin her graduate studies in Fall 2012 in geophysics.

MICHAEL H. MOLONEY is the director of the SSB and the Aeronautics and Space Engineering Board at the NRC. Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy (BPA), the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Before joining the SSB and ASEB in April 2010, he was associate director of the BPA and study director for the Astro2010 decadal survey for astronomy and astrophysics. In addition to his professional experience at the NRC, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government and served in that capacity at the Embassy of Ireland in Washington, D.C., the Mission of Ireland to the United Nations in New York, and the Department of Foreign Affairs in Dublin, Ireland. A physicist, Dr. Moloney did his graduate Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

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Acronyms and Abbreviations

3D-WINDS	3D Tropospheric Winds from Space-based Lidar
4STAR	Spectrometer for Sky-Scanning, Sun-Tracking Atmospheric Research (for $SEAC^4RS$)
ABACATE	Airborne Biodiversity Assessment of Coastal and Terrestrial Ecosystems
ACE	Aerosol/Cloud/Ecosystems [Missions]
ACRIMSAT	Active Cavity Radiometer Irradiance Monitor Satellite
ADM	Atmospheric Dynamics Mission
AERONET	Aerosol Robotic Network
AID	Aircraft Instrument Demonstration
AIRS	Atmospheric Infrared Sounder
Aladin	Atmospheric Laser Doppler-Lidar Instrument
ALT	[Ocean] Altimeter
AMSR-E	Advanced Microwave Scanning Radiometer-EOS
APS	Advanced Polarimetry Sensor
ARCTAS	Arctic Research of the Composition of the Troposphere from Aircraft and Satellites
ARRA	American Recovery and Reinvestment Act
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATMS	Advanced Technology Microwave Sounder
AVIRIS CONUS	Airborne Visible/Infrared Imaging Spectrometer [over the] continental United States

CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAR	Cloud Absorption Radiometer
CASIE	Characterization of Arctic Sea Ice Experiment
CC-VEX	Calipso and CloudSat Validation Experiment
CERES	Clouds and Earth's Radiant Energy System
CIESEN	Center from International Earth Science Information Network
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CLASIC	Cloud and Land Surface Interaction Campaign
CLPXII	Cold Land Processes Field Experiment (II)
CMIS	Conical Microwave Imager/Sounder
CNES	Centre National d'Études Spaciales
CONAE	Comision Nacional de Actividades Espaciales
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate; aka FORMOSAT
CrIS	Cross-track Infrared Sounder
CTM	Chemistry and Transport Model
DESDynI	Deformation, Ecosystem Structure, and Dynamics of Ice
DFS	Dual-frequency Scatterometer
DISCOVER-AQ	Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality
DLR	German Aerospace Center
DOD	Department of Defense
DOI	Department of the Interior
DPR	Dual-Frequency Precipitation Radar
DSCOVR	Deep Space Climate Observatory
DWSS	Defense Weather Satellite System
ECMWF	European Centre from Medium Range Weather Forecasts
EDU	Engineering Development Unit
EELV	Evolved Expendable Launch Vehicle
EO-1	Earth Observing Mission-1
EOS	Earth Observing System
EOSDIS	Earth Observing System Data and Information System
ERB	Earth Radiation Budget
ERBS	Earth Radiation Budget Sensor
ESA	European Space Agency
ESAS	Earth Science and Applications from Space
ESD	Earth Science Division

ESE	Earth Science Enterprise
ESPO	Earth Science Program Office
ESTO	Earth Science Technology Office
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EV	Earth Venture
FEMA	Federal Emergency Management Agency
FNMOC	U.S. Navy's Fleet Numerical Meteorology and Oceanography Center
FORMOSAT	See COSMIC
GACM	Global Atmospheric Composition Mission
GCOM-C	Global Change Observation Mission-Climate
GCOM-W	Global Change Observation Mission-Water
GEO-CAPE	Geostationary Coastal and Air Pollution Events [mission]
GIFTS	Geosynchronous Imaging Fourier Transfer System
GLEAM	Great Lakes Environmental Assessment and Mapping [Project]
GloPac	Global Hawk Pacific
GMAO	Global Modeling and Assimilation Office
GMI	GPM Microwave Imager
GNSS	Global Navigation Satellite System
GODAE	Global Ocean Data Assimilation Office
GOES-R	Geostationary Orbit Environmental Satellite-R Series
GOSAT	Greenhouse Gas Observing Satellite
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GPSRO	Global Positioning System Radio Occultation
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment-Follow On
GRACE-II	Gravity Recovery and Climate Experiment-II
GRIP	Genesis and Rapid Intensification Process
GWE	Global Weather Experiment
HES	Hyperspectral Environmental Suite
HEX	Hydrometeorological Experiment
HICO	Hyperspectral Imager for the Coastal Ocean
HyspIRI	Hyperspectral Infrared Imager
IASI	Infrared Atmospheric Sounding Interferometer
ICECAP	Investigating the Crysopheric Evolution of the Central Antarctic Plate

ICESat-2	Ice, Cloud, and land Elevation Satellite
ICSU	International Council of Scientific Unions
INTEX-B	Intercontinental Chemical Transport Experiment Phase B
IPO	Integrated Program Office
ISCCP	International Satellite Cloud Climatology Project
ISS	International Space Station
JASD	Joint Agency Satellite Division
JAXA	Japan Aerospace Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JEM-EF	Japanese Experiment Module-Exposed Facility
JPSS	Joint Polar Satellite System
LASP	Laboratory for Atmospheric and Space Physics
LCLUC	Land Cover/Land Use Change
LDCM	Landsat Data Continuity Mission
LIO	Low-Inclination Orbiter
LIST	Lidar Surface Topography
MACPEX	Mid-latitude Airborne Cirrus Properties Experiment
MAP	Modeling, Analysis, and Prediction
MAPEX	Midlatitude Airborne Cirrus Properties Experiment
MERRA	Modern Era Retrospective-Analysis for Research and Applications
MILAGRO	Megacity Initiative: Local and Global Research Observations
MODIS	Moderate-Resolution Imaging Spectroradiometer
MOE	Mission Operations Element
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite Data and Information Service
NLS	NASA Launch Services
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NWS	National Weather Service
OCO	Orbiting Carbon Observatory
OIB	Operation IceBridge
OLI	Operational Land Imager

OMB	Office of Management and Budget
OMPS	Ozone Monitoring and Profiling Suite
ONR	Office of Naval Research
OSC	Orbital Sciences Corporation
OSSE	Observing System Simulation Experiment
OSTM	Ocean Surface Topography Mission
OSTP	Office of Science and Technology Policy
PACE	Pre-Aerosol, Clouds, and ocean Ecosystem
PATH	Precipitation and All-weather Temperature and Humidity
POC	Point of Contact
QuikSCAT	Quick Scatterometer
R&A	Research and Analysis
ROSES	Research Opportunities in Space and Earth Sciences
SAC[-D]	Satélite de Aplicaciones Científicas
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar
SCLP	Snow and Cold Land Processes
SEAC^{4}RS	Southeast Asia Composition, Cloud, Climate Coupling Regional Study
SEDAC	Socioeconomic Data and Applications Center
SIMPL	Slope Imagine Multi-polarization Photon-counting Lidar
SMAP	Soil Moisture Active-Passive
SMAPVEX	Soil Moisture Active-Passive-Validation Experiment
SMD	[NASA] Science Mission Directorate
SLR	Satellite Laser Ranging
SORCE	Solar Radiation and Climate Experiment
SPoRT	Short-Term Prediction and Research Transition Center
SWOT	Surface Water and Ocean Topography
TC-4	Tropical Composition, Cloud and Climate Coupling
TCCON	Total Carbon Column Observing Network
TIM	Total Irradiance Monitor
TIRS	Thermal Infrared Sensors
TOPEX	Ocean Topography Experiment
TRMM	Tropical Rainfall Measuring Mission

TSI	Total Solar Irradiance
TSIS	Total Solar Irradiance Sensor
UAS	Unmanned Aircraft System
UAV	Uninhabited Aerial Vehicle
UAVSAR	Uninhabited Aerial Vehicle Synthetic Aperture Radar
ULA	United Launch Alliance
USDA	U.S. Department of Agriculture
USGEO	U.S. Group on Earth Observations
USGS	U.S. Geological Survey
VIRS	Visible and Infrared Scanner
VLBI	Very Long Baseline Interferometry
XOVWM	Extended Ocean Vector Winds Mission