Free Executive Summary

Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond

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

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Executive Summary

A 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.

These declarations, first made in the interim report of the Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future,[1] are the foundation of the committee's vision for a decadal program of Earth-science research and applications in support of society—a vision 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. The declarations call for a renewal of the national commitment to a program of Earth observations in which attention to securing practical benefits for humankind play an equal role with the quest to acquire new knowledge about the Earth system.

The committee strongly reaffirms these declarations in the present report, which completes the National Research Council's (NRC's) response to a request from the National Aeronautics and Space Administration (NASA) Office of Earth Science, the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite Data and Information Service, and the U.S. Geological Survey (USGS) Geography Division to generate consensus recommendations from the Earth and environmental science and applications communities regarding (1) high-priority flight missions and activities to support national needs for research and monitoring of the dynamic Earth system during the next decade, and (2) important directions that should influence planning for the decade beyond.[2] The national strategy outlined here has as its overarching objective a program of scientific discovery and development of applications that will enhance economic competitiveness, protect life and property, and assist in the stewardship of the planet for this and future generations.

Earth observations from satellites and in situ collection sites are critical for an ever-increasing number of applications related to the health and well-being of society. The committee found that fundamental improvements are needed in existing observation and information systems because they only loosely connect three key elements: (1) the raw observations that produce information; (2) the analyses, forecasts, and models that provide timely and coherent syntheses of otherwise disparate information; and (3) the decision processes that use those analyses and forecasts to produce actions with direct societal benefits.

Taking responsibility for developing and connecting these three elements in support of society's needs represents a new social contract for the scientific community. The scientific community must focus on meeting the demands of society explicitly, in addition to satisfying its curiosity about how the Earth system works. In addition, the federal institutions responsible for the Earth sciences' contributions to

[1] National Research Council (NRC), *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*, The National Academies Press, Washington, D.C., 2005. Referred to hereafter as the "interim report."

[2] The other elements of the committee's charge are shown in Appendix A. As explained in the Preface, the committee focused its attention on items 2, 3, and 4 of the charge.

protection of life and property, strategic economic development, and stewardship of the planet will also need to change. In particular, the clarity with which Congress links financial resources with societal objectives and provides oversight to ensure that these objectives are met, must keep pace with emerging national needs. Individual agencies must develop an integrated framework that transcends their particular interests, with clear responsibilities and budget authority for achieving the most urgent societal objectives. Therefore, the committee offers the following overarching recommendation:

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.

The objectives of these partnerships would be to facilitate improvements that are needed in the structure, connectivity, and effectiveness of Earth observing capabilities, research, and associated information and application systems—not only to answer profound scientific questions, but also to effectively apply new knowledge in pursuit of societal benefits.

The world faces significant environmental challenges: shortages of clean and accessible freshwater, degradation of terrestrial and aquatic ecosystems, increases in soil erosion, changes in the chemistry of the atmosphere, declines in fisheries, and the likelihood of substantial changes in climate. These changes are not isolated; they interact with each other and with natural variability in complex ways that cascade through the environment across local, regional, and global scales. Addressing these societal challenges requires that we confront key scientific questions related to ice sheets and sea level change, large-scale and persistent shifts in precipitation and water availability, transcontinental air pollution, shifts in ecosystem structure and function in response to climate change, impacts of climate change on human health, and occurrence of extreme events, such as severe storms, heat waves, earthquakes, and volcanic eruptions. The key questions include:

- Will there be catastrophic collapse of the major ice sheets, including Greenland and West Antarctic and, if so, how rapidly will this occur? What will be the time patterns of sea level rise as a result?
- Will droughts become more widespread in the western U.S., Australia, and Sub Saharan Africa? How will this affect the patterns of wildfires? How will reduced amounts of snowfall change the needs for water storage?
- How will continuing economic development affect the production of air pollutants, and how will these pollutants be transported across oceans and continents? How are these pollutants transformed during the transport process?
- How will coastal and ocean ecosystems respond to changes in physical forcing, particularly those subject to intense human harvesting? How will the boreal forest shift as temperature and precipitation change at high latitudes? What will be the impacts on animal migration patterns and invasive species?
- Will previously-rare diseases become common? How will mosquito-borne viruses spread with changes in rainfall and drought? Can we better predict the outbreak of avian flu? What are the health impacts of an expanded "Ozone Hole" that could result from a cooling of the stratosphere, which would be associated with climate change?
- Will tropical cyclones and heat waves become more frequent and more intense? Are major fault systems nearing release of stress via strong earthquakes?

The required observing system is one that builds upon the current fleet of space-based instruments and brings us to a new level of integration in our understanding of the Earth system.

SETTING THE FOUNDATION: OBSERVATIONS IN THE CURRENT DECADE

As documented in this report, the United States' extraordinary foundation of global observations is at great risk. 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.1a and ES.1b). Furthermore, the replacement sensors to be flown on the National Polar-orbiting Operational Environmental Satellite System (NPOESS),[3] are generally less capable than their Earth Observing System (EOS) counterparts.[4] Among the many measurements expected to cease over the next few years, the committee has identified several that are providing critical information now which 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 total solar irradiance and Earth radiation, vector sea surface winds, limb sounding of ozone profiles, and temperature and water vapor soundings from geostationary and polar orbits.[5]

As highlighted in the committee's interim report, there is substantial concern that substitution of passive microwave sensor data for active scatterometry data will worsen El Niño and hurricane forecasts and weather forecasts in coastal areas.[6] Given the status of existing surface wind measurements and the substantial uncertainty introduced by the cancellation of the CMIS instrument on NPOESS, the committee believes it imperative that a measurement capability be available to prevent a data gap when the NASA QuikSCAT mission, already well past its nominal mission lifetime, terminates.

Questions about the future of wind measurement capabilities are part of a larger set of issues related to the development of a "mitigation strategy" to recover capabilities lost in the recently announced descoping and cancellations of instruments and spacecraft planned for the NPOESS constellation. A request for the committee to perform a fast track analysis of these issues was approved by the NRC shortly before this report went to press. Nevertheless, based on its analysis to date, the committee makes the following recommendations:

[3] See description at <http://www.ipo.noaa.gov/>.

[4] NASA's Earth Observing System (EOS) includes a series of satellites, a science component, and a data system supporting a coordinated series of polar-orbiting and low inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans. See http://eospso.gsfc.nasa.gov/eos_homepage/description.php.

[5] As discussed in the preface and in more detail in Chapter 2, the continuity of a number of other critical measurements, such as sea surface temperature, is dependent on the acquisition of a suitable instrument on NPOESS to replace the now- canceled CMIS sensor.

[6] Also, see pp.4-5 of the Oceans Community Letter to the Decadal Survey, http://cioss.coas.oregonstate.edu/CIOSS/Documents/Oceans_Community_Letter.pdf and the report of the NOAA Operational Ocean Surface Vector Winds Requirements Workshop, National Hurricane Center, Miami, FL, June 5-7, 2006, P. Chang and Z. Jelenak, eds.

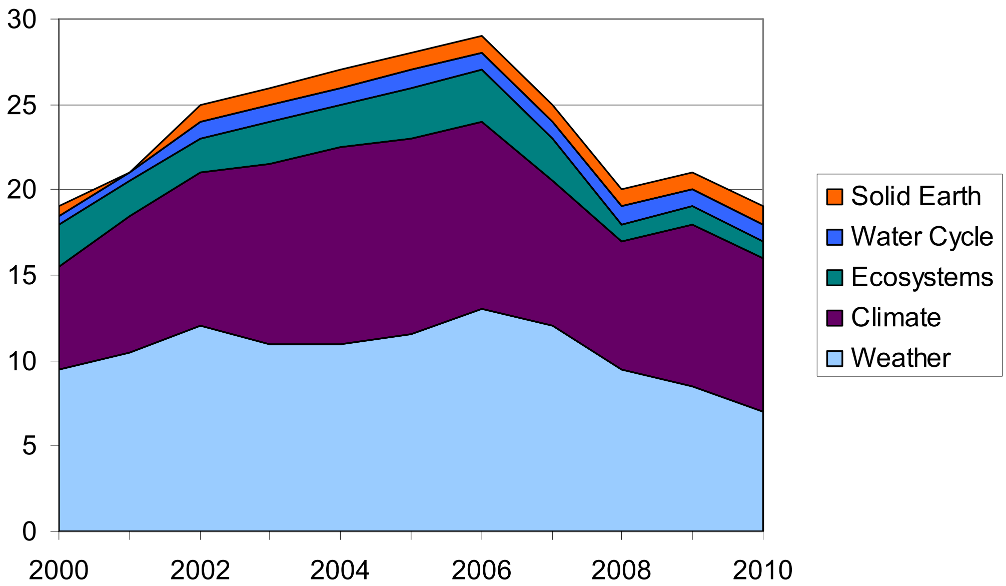

FIGURE ES.1a Number of U.S. space-based Earth Observations missions in the current decade. An emphasis on climate and weather is evident, as is the decline in number of missions near the end of the decade. For the period from 2007 to 2010, missions were generally assumed to operate for four years past their nominal lifetimes. Most of the missions were deemed to contribute at least slightly to human health issues and so health is not presented as a separate category. SOURCE: NASA and NOAA websites for mission durations.

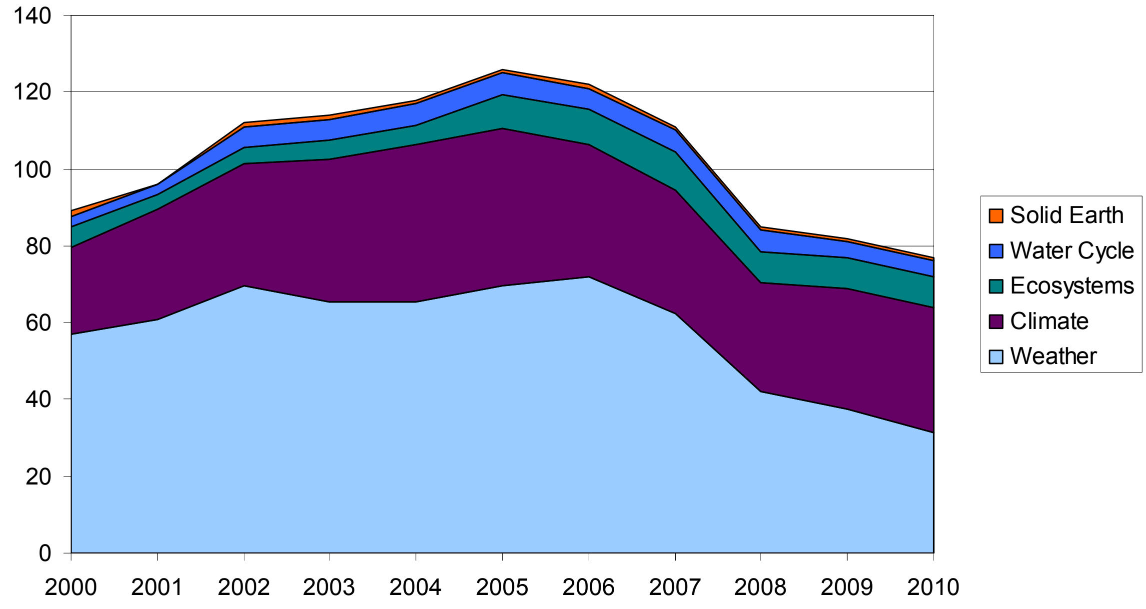

FIGURE ES.1b Number of U.S. space-based Earth Observations instruments in the current decade. Emphasis on climate and weather is evident as is the decline in number of instruments near the end of the decade. For the period from 2007 to 2010, missions were generally assumed to operate for four years past their nominal lifetimes. Most of the missions were deemed to contribute at least slightly to human health issues and so health is not presented as a separate category. SOURCE: Information from NASA and NOAA websites for mission durations.

Recommendation: NOAA should restore several key climate, environmental, and weather observation capabilities to its planned NPOESS and GOES-R[7] missions; namely:

- **Measurements of total solar irradiation and Earth radiation recently eliminated from NPOESS should be restored on NPOESS or provided by other means to avoid a measurement gap in the timeframe 2008 to 2012.**
- **Passive measurements of ocean vector winds and all-weather sea surface temperatures descoped from NPOESS C1 launch should be restored, or obtained by other means, to provide continuity until the CMIS replacement is operational on NPOESS C2 and higher-quality active scatterometer measurements 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.[8]**

The committee also recommends that NOAA:

- **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.**

These measurements were originally to be delivered via 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:

1. **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**
2. **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 committee believes such approaches will strengthen both the technological foundation of GEO-based soundings and provide the requisite experience for efficient operational implementation of GEO-based soundings.

The recommendations above focus on issues whose resolution requires action by NOAA. The committee also notes two issues of near-term concern mostly for NASA:

1. Understanding the changing global precipitation patterns that result from changing climate, and
2. Understanding the changing patterns of land-use due to the needs of a growing population, the expanding and contracting of economies, and intensification of agriculture.

[7] GOES-R is the designation for the next generation of geostationary operational environmental satellites (GOES). See <https://osd.goes.noaa.gov//> and <http://goespoes.gsfc.nasa.gov/goes/spacecraft/r_spacecraft.html>. The first launch of the GOES-R series satellite was recently delayed from the 2012 timeframe to December 2014.

[8] Without this capability, no national or international ozone profiling capability will exist after EOS Aura (mission end 2010). This capability is key to monitoring ozone layer recovery in the next two decades, and is part of NOAA's mandate through the Clean Air Act.

Both of these concerns have been highlighted in the scientific and policy literature;[9] they were also highlighted in committee's interim report. The committee believes that it is vital to maintain global precipitation measurements as offered by GPM, and to continue to document biosphere changes, which have been provided measurements from instruments on the Landsat series of spacecraft.

Recommendation: NASA should ensure continuity of measurements of precipitation and land cover by:

- **Launching GPM in or before 2012.**
- **Securing a replacement to Landsat 7 data before 2012.**

The committee also recommends that NASA continue to seek cost-effective, innovative means for obtaining land cover change information.

Sustained measurements of these key climate and weather variables are part of the committee's strategy to achieve its vision for Earth information in the next decade. The new recommended observational system that will help deliver that vision is described next.

NEW OBSERVATIONS FOR THE NEXT DECADE

The primary work in developing the decadal observing strategy took place within the survey's seven thematically-organized science panels (see Preface). Six of the panels were organized to address multi-discipline issues in the general areas of climate change, water resources, ecosystem health, human health, solid-Earth natural hazards, and weather. This categorization is quite similar to the organizing structure used in the GEOSS process. Each panel first prioritized a wide range of candidate space-based measurement approaches and mission concepts by applying the criteria shown in Box ES.1. The assessment and subsequent prioritization were based on an overall analysis by panel members as to how well each mission satisfied the criteria and high-level community objectives. Recommendations from previous community-based reports such as those from the World Meteorological Organization were also considered.

The complete set of high priority observations/missions identified by the panels numbered approximately 35, a substantial reduction from the over 100 missions suggested in the responses to the committee's Request for Information (RFI—see Appendix D) and numerous other mission possibilities raised by individual panel members (see Table 2.4). The panel reports in Part III of this report document this analysis.

In establishing this set of missions, the committee recognized that a successful program is more than the sum of its parts. The committee's prioritization methodology was designed to achieve a robust, integrated program—one that does not crumble if one or several missions in the prioritized list are removed or delayed or if the mission list must evolve to accommodate changing needs. The methodology was also intended to enable augmentation of an enhanced the program should additional resources become available beyond those anticipated by the committee. Robustness is thus measured by the strength of the overall program, not by the particular missions on the list**.** It is the range of observations that must be protected rather than the individual missions themselves.

[9] For example, see the IPCC Third Assessment Report: Climate Change 2001, which are available at <http://www.ipcc.ch/pub/reports.htm> or <http://www.grida.no/climate/ipcc_tar/> and the 2005 Millennium Ecosystem Assessment Synthesis Reports, which are available at < http://www.maweb.org/en/Products.aspx?>.

The committee's recommended observational strategy consists of:

- 14 missions for implementation by NASA,
- 2 missions for implementation by NOAA, and
- 1 mission (CLARREO), which has separate components for implementation by NASA and NOAA

These 17 missions are summarized in Tables ES.1 (NOAA portion) and ES.2 (NASA portion). The suggested observing strategy is consistent with the recommendations from the U.S. Global Change Research Program (USGCRP), the U.S. Climate Change Science Program (CCSP), and the U.S. component of the Global Earth Observation System of Systems (GEOSS). Most importantly, the observing strategy enables major progress across the range of important societal issues. The number of recommended missions and associated observations is only a fraction of the number of currently operating Earth missions and observations (see Figures ES.1a and ES.1b). *The committee believes strongly that these missions form a minimal, yet robust, observational component of an Earth information system that is capable of addressing a broad range of societal needs.*

Recommendation: In addition to implementing the re-baselined NPOESS and GOES program and completing research missions currently in development, NASA and NOAA should undertake a set of 17[10] recommended missions (Tables ES.1 and ES.2), comprised of small (<$300 million), medium ($300 million to $600 million), and large ($600 million to $ 900 million) cost missions, and phased appropriately over the next decade.[11] Larger facility-class (>$1 billion) missions are not recommended. As part of this strategy:

- **NOAA should transition three research observations to operations, as recommended in Table ES.1. 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 XOVWM, GPSRO, and CLARREO missions recommended in this report.**
- **NASA should implement a set of 15 missions with small (<$300 million), medium ($300 million to $600 million), and large ($600 million to $900 million) cost ranges. These missions should be phased over the next decade. All of the appropriate LEO missions should include a GPS receiver to augment operational measurements of temperature and water vapor. The missions and their specifications are given in Table ES.2.**

In developing its plan, the committee exploited both science and measurement synergies among the various priority missions of the individual panels to create a more capable and affordable observing system. For example, the committee recognized that ice sheet change, solid-Earth hazards, and ecosystem health objectives are together well-addressed by a combination of radar and lidar instrumentation. As a result, a pair of missions, flying in the same timeframe was devised to address the three societal issues.

The phasing of missions over the next decade was primarily driven by consideration of the maturity of key prediction and forecast tools and the timing of particular observations needed for either maintaining or improving those tools. For established applications, with a clear operational use, such as

[10] One mission, CLARREO, has two components – a NASA component and a separate NOAA component.
[11] Tables ES.1 and ES.2 include cost estimates for the 17 missions. These estimates include costs for development, launch, and 3 years of operation for NASA research missions and 5 years of operation for NOAA operational missions. Estimates also include funding of a science team to work on algorithms and data preparation, but not for "research and analysis" efforts to extract science from the data. Note: All estimates are in fiscal year 2006 dollars.

numerical weather prediction (NWP), the need for routine vector sea surface wind observations and atmospheric temperature and water vapor soundings by relatively mature instrument techniques set the early phasing and are recommended to NOAA for implementation. For less mature applications, such as for earthquake forecasting and mitigation models, the committee recommends obtaining new surface deformation observations early in the decade in order to accelerate tool improvements. Observations of this type, being more research-oriented, are recommended to NASA for implementation.

TABLE ES.1 Launch, orbit, and instrument specifications for the recommended NOAA missions. Shade colors denote mission cost categories as estimated by the NRC ESAS committee. Green and blue shadings represent medium ($300 million to $600 million) and small (<$300 million) missions, respectively. Detailed descriptions of the missions are given in Part II, and Part III provides the foundation for selection.

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost Estimate
Timeframe 2010 - 2013—Missions listed by cost				
CLARREO (Instrument Re-flight Components)	Solar and Earth radiation characteristics for understanding climate forcing	LEO, SSO	Broadband radiometers	$65 M
GPSRO	High accuracy, all-weather temperature, water vapor, and electron density profiles for weather, climate and space weather	LEO	GPS receiver	$150 M
Timeframe 2013 – 2016				
XOVWM	Sea surface wind vectors for weather and ocean ecosystems	LEO, SSO	Backscatter radar	$350 M

TABLE ES.2 Launch, orbit, and instrument specifications for the recommended NASA missions. Shade colors denote mission cost categories as estimated by the NRC ESAS committee. Pink, green, and blue shadings represent large ($600 million to $900), medium ($300 million to $600 million), and small (<$300 million) missions, respectively. Missions are listed in order of ascending cost within each launch timeframe. Detailed descriptions of the missions are given in Part II, and Part III provides the foundation for selection.

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost Estimate
Timeframe 2010 – 2013, Missions listed by cost				
CLARREO (NASA portion)	Solar radiation: spectrally resolved forcing and response of the climate system	LEO, Precessing	Absolute, spectrally-resolved interferometer	$200 M
SMAP	Soil moisture and freeze/thaw for weather and water cycle processes	LEO, SSO	L-band radar L-band radiometer	$300 M
ICESat-II	Ice sheet height changes for climate change diagnosis	LEO, Non-SSO	Laser altimeter	$300 M
DESDynI	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	LEO, SSO	L-band InSAR Laser altimeter	$700 M
Timeframe: 2013 – 2016, Missions listed by cost				
HyspIRI	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	LEO, SSO	Hyperspectral spectrometer	$300 M
ASCENDS	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	LEO, SSO	Multifrequency laser	$400 M
SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	LEO, SSO	Ka-band wide swath radar C-band radar	$450 M
GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	GEO	High and low spatial resolution hyperspectral imagers	$550 M
ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	LEO, SSO	Backscatter lidar Multiangle polarimeter Doppler radar	$800 M
Timeframe: 2016 -2020, Missions listed by cost				
LIST	Land surface topography for landslide hazards and water runoff	LEO, SSO	Laser altimeter	$300 M
PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST[a]	GEO	MW array spectrometer	$450 M
GRACE-II	High temporal resolution gravity fields for tracking large-scale water movement	LEO, SSO	Microwave or laser ranging system	$450 M
SCLP	Snow accumulation for fresh water availability	LEO, SSO	Ku and X-band radars K and Ka-band radiometers	$500 M
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	$600 M
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	$650 M

[a] Cloud-independent, high temporal resolution, lower accuracy SST to complement, not replace, global operational high accuracy SST measurement.

BOX ES.1 PRIORITIZATION CRITERIA USED BY THE PANELS TO CREATE RELATIVE RANKINGS OF MISSIONS

1. Contribution to the most important scientific questions facing Earth sciences today (scientific merit, discovery, exploration).
2. Contribution to applications and policy making (societal benefits).
3. Contribution to long-term observational record of the Earth.
4. Ability to complement other observational systems, including national and international plans.
5. Affordability (cost considerations, either total costs for mission or costs per year).
6. Degree of readiness (technical, resources, people).
7. Risk mitigation and strategic redundancy (backup of other critical systems).
8. Significant contribution to more than one thematic application or scientific discipline.

Note that these are guidelines; they are not in priority order, and they may not reflect all of the criteria considered by the panels.

In setting the mission timing, the committee also considered mission costs relative to what it considered reasonable future budgets, technology readiness, and the potential of international missions to provide alternative sources of select observations. Rough cost estimates and technology readiness information for proposed missions were provided to the committee by NASA or culled from available information on current missions. The committee decided not to include possible cost sharing by international partners as such relationships are sometimes difficult to quantify. Such sharing could reduce significantly the costs of the missions to the United States.

Given the relatively large uncertainties attached to cost and technology readiness estimates, the committee chose to sequence missions among three broad decadal periods, namely, 2010-2013, 2013-2016, and 2016-2020. Missions seen to require significant technology development, such as high power, multi-frequency lasers, for 3-D winds and aerosol and ozone profiling, and thin-array microwave antennas and receivers for temperature and water vapor soundings, were targeted for either mid or late periods of the next decade; the exact placement depended on the perceived scientific and forecasting impact of the considered observation (see Chapter 2).

Large uncertainties are also associated with attempts to factor in international partner missions in the timing of U.S. missions during the next decade. For example, at the beginning of the next decade, there are international plans for the GCOM-C (2011) and EarthCARE (2012), missions that are aimed at observing aerosol and clouds. As a result, the committee targeted a later time for a U.S. mission to explore cloud and aerosol interactions. The ESA Earth Explorer program has also recently selected six mission concepts for Phase A studies, from which it will select one or two for launch in ~2013. All of the Phase A study concepts carry potential value for the broader Earth science community and provide overlap with missions recommended by this committee. Accordingly, the committee recognizes the importance of maintaining flexibility in the NASA observing program to leverage possible international activities, either by appropriate sequencing of complementary NASA and international partner missions or by exploring possible combinations of appropriate U.S. and international-developed instruments on various launch opportunities.

The set of recommended missions listed in Tables ES.1 and ES. 2 reflects an integrated, cohesive, and carefully sequenced mission plan that addresses the range of urgent societal benefit areas. While the launch order of the missions represents, in a practical sense, a priority order, it is important to recognize that the many factors involved in developing the mission plan preclude such a simple prioritization (see discussion in Chapter 3 and decision strategies summarized in Box ES.2).

BOX ES.2 PROGRAMMATIC DECISION STRATEGIES AND RULES

Leverage International Efforts

- Restructure or defer missions if international partners select missions which meet most of the measurement objectives of the recommended missions, then a) through dialogue establish data access agreements, and b) 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 significantly less cost to the partners.

Manage Technology Risk

- Sequence missions according to technological readiness and budget risk factors. The budget risk consideration may give a bias to initiating lower cost missions first. However, technological 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 timeframes, it is still important to make advances on the key technological hurdles.
- Establish technological readiness through documented technology demonstrations before mission development phase, and certainly before mission confirmation.

Respond to Budget Pressures and Shortfalls

- Delay downstream missions in the event of small (~10%) cost growths in mission development. Protect the overarching observational program by canceling missions that substantially overrun.
- Implement a system-wide independent review process such that decisions regarding technical capabilities, cost, and schedule are made in the context of the overarching scientific objectives. Thus, programmatic decisions on potential delays or reductions in capabilities of a particular mission will 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 within each theme area rather than whole themes.
- ***In the event of budget shortfalls,*** re-evaluate the entire set of missions given 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 terms 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.

The recommended missions for NASA do not fit neatly within the existing structure of Systematic (i.e., strategic and/or continuous measurements typically assigned to a NASA center for implementation) and ESSP (i.e., exploratory measurements that are competed community-wide) mission lines. The committee considers all of the recommended missions to be "strategic" in nature, but recognizes that some of the less complex and technically challenging missions could be competed rather than assigned. The committee notes that historically the broader Earth science research community's involvement in conducting space-borne missions has been almost exclusively in concert with various implementing NASA centers. Accordingly, the committee advises NASA to seek to implement this set of recommended missions as part of one strategic program, or mission line, using both competitive and non-competitive methods to create a timely and effective program.

The observing system envisioned here will help establish a firm and sustainable foundation for Earth science and associated societal benefits in the year 2020 and beyond. It will be achieved through effective management of technology advances and international partnerships, and broad use of the space-based science data by the research and decision-making communities. In looking beyond the next decade, the committee recognizes the need to learn lessons from implementation of the 17 recommended missions *and* to efficiently transition select research observations to operational status. These steps will create new space-based observing opportunities, foster new science leaders, and facilitate the implementation of revolutionary ideas. Towards these objectives, the committee makes the following recommendation:

Recommendation: U.S. civil space agencies should aggressively pursue technology development that supports the recommended missions; plan for transitions to continue demonstrably useful research observations on a sustained, or operational, basis; and foster innovative new space-based concepts. In particular:

- **NASA should increase investment in both mission-focused and cross-cutting technology development in order 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.**
- **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 M - $200M). These missions should focus on fostering revolutionary innovation and training future leaders of space-based Earth science and applications.**
- **NOAA should increase investment in identifying and facilitating the transition of demonstrably useful research observations to operational use.**

The Venture class of missions, in particular, would replace, and be very different from the current Earth System Science Pathfinder (ESSP) mission line, which increasingly has become a competitive means for implementing NASA's strategic missions. Priority would be given to cost-effective, innovative missions rather than ones with excessive scientific and technological requirements. The Venture class could include stand-alone missions using simple, small instruments/spacecraft/launch vehicles, more complex instruments of opportunity flown on partner spacecraft/launch vehicles, or complex sets of instruments flown on suitable suborbital platforms to address focused sets of scientific questions. The focus of these missions can be on establishing entirely new research avenues or in demonstrating key application-oriented measurements. A key to the success of this program is to maintain a steady stream of opportunities for community participation in innovative idea development. This requires that strict schedule and cost guidelines be enforced on the program participants.

TURNING SATELLITE OBSERVATIONS INTO KNOWLEDGE AND INFORMATION

Translating raw observations of Earth into useful information requires sophisticated scientific and applications techniques. The recommended mission plan is but one part of this larger program, all elements of which must be executed if the overall Earth research and applications enterprise is to succeed. The objective is to establish a program that is effective in its use of resources, resilient to the evolving constraints within which any program must operate, and able to embrace new opportunities as they arise. Among the key additional elements of the overall program that must be supported to achieve the decadal vision are: (1) sustained observations from space for research and monitoring, (2) surface-based and airborne observations that are necessary for a complete observing system; (3) models and data assimilation systems that allow effective use of the observations to make useful analyses and forecasts, and (4) planning and other activities that strengthen and sustain the knowledge and information system.

Obtaining observations that serve the range of science and societal challenges requires a hierarchy of measurement types, spanning from first-ever exploratory measurements, to long-term, continuous measurements. Long-term observations can be primarily focused on scientific challenges (*sustained* observations) or specific societal applications (*operational* measurements). There is connectivity between sustaining research observations and operational systems. Though operational systems perform forecasting or monitoring functions, the observations and products from operational systems, such as weather forecasts, are also useful for a many research purposes. Similarly, sustained observations, while focused on research questions, clearly include an aspect of monitoring, and may be used operationally. While exploratory, sustained, and operational measurements often share the need for new technology, careful calibration, and long-term stability, there are also important differences among them. Thus, exploratory, sustained, and operational Earth observations are distinct and overlapping categories.

An efficient and effective Earth observation system requires an ongoing interagency evaluation of the capabilities and potential applications of numerous current and planned missions for transition of fundamental science missions into operational observation programs. *The committee is particularly concerned with the lack of clear agency responsibility for sustained research programs and the transitioning of proof-of-concept measurements into sustained measurement systems.* To address societal and research needs, both the quality and the continuity of the measurement record must be assured through the transition of short-term, exploratory capabilities, into sustained observing systems. Transition failures have been exhaustively described in previous reports and the committee endorses the recommendations in these studies.[12]

The elimination of the requirements for climate research-related measurements on NPOESS is only the most recent example of the nation's failure to sustain critical measurements. The committee notes that despite NASA's involvement in climate research and its extensive development of measurement technology to make climate-quality measurements, the agency has no requirement for extended measurement missions, except for ozone measurements, which are explicitly mandated by Congress. **Therefore, the committee endorses the recommendation of a recent NRC 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."**[13]

The committee is concerned that the nation's institutions involved in civil space (including NASA, NOAA, and USGS) are not adequately prepared to meet society's rapidly evolving Earth

[12] NRC, *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death,* The National Academy Press, Washington, D.C., 2000 and NRC, *Satellite Observations of the Earth's Environment-Accelerating the Transition of Research to Operations,* The National Academies Press, Washington, D.C., 2003.

[13] NRC, *A Review of NASA's 2006 Draft Science Plan: Letter Report*, The National Academies Press, Washington, D.C., 2006.

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 government. Thus, the committee makes the following recommendation:

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.

The space-based observations recommended by the committee will provide a global view of many Earth system processes. However, satellite observations have spatial and temporal resolution limitations and hence do not alone provide a picture of the Earth system that is sufficient for understanding all of the key physical, chemical, and biological processes. In addition, satellites do not directly observe many of the changes in human societies that are impacted by, or will affect, the environment. In order to build the requisite knowledge for addressing urgent societal issues, data are also needed from suborbital and land-based platforms, as well as from socio-demographic studies. The committee finds that greater attention is needed to the entire chain of observations to research to applications and benefits. Regarding complementary observations, the committee makes the following recommendation:

Recommendation:

- **Earth system observations should be accompanied by a complementary system of observations of human activities and their effects on Earth, and**
- **Socioeconomic factors should be considered in the planning and implementation of Earth observation missions and in developing the Earth Information System.**

To facilitate synthesis of scientific data and scientific discovery into coherent and timely information for end-users, the committee makes the following recommendation:

Recommendation: NASA should support Earth science research via suborbital platforms: airborne programs, which have suffered substantial diminution, should be restored, and UAV technology should be increasingly factored into the nation's strategic plan for Earth sciences.

There is also a myriad of steps necessary for providing quantitative information, analyses, and predictions for important geophysical and socioeconomic variables over the range of needed time scales. The value of the recommended missions will only be realized through a high-priority and complementary focus on modeling, data assimilation, data archive and data distribution, and research and analysis.[14] To this end, the committee makes the following recommendations:

[14] NASA's research and analysis program ("R&A") has customarily supplied funds for enhancing fundamental understanding in a discipline and stimulating the questions from which new scientific investigations flow. R&A studies also enable conversion of raw instrument data into fields of geophysical variables and are an essential component in support of the research required to convert data analyses to trends, processes, and improvements in simulation models. They are likewise necessary for improving calibrations and evaluating the limits of both remote and in situ data. Without adequate R&A, the large and complex task of acquiring, processing, and archiving geophysical data would go for naught. Finally, the next generation of Earth scientists—the graduate students in universities—are often educated by performing research that has originated in R&A efforts. See NRC, *Earth*

Recommendations:

- **Teams of experts should be formed to consider assimilation of data from multiple sensors and all sources, including commercial providers and international partners.**
- **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.**
- **As new Earth observation missions are developed, there must also be early attention 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.**
- **NASA should increase support of its Research and Analysis (R&A) program to a level commensurate with its ongoing and planned missions. Further, in light of the need for both a healthy R&A program that is not mission-specific, as well as the need for mission-specific R&A, the committee recommends to NASA that space-based missions should have adequate R&A lines within the mission 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.**
- **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.**

SUSTAINING THE KNOWLEDGE AND INFORMATION SYSTEM

A successful Earth information system needs to be planned and implemented around long-term strategies that encompass the lifecycle from research to operations to applications. The strategy must include nurturing an effective workforce, informing the public, sharing in development of a robust professional community, ensuring effective and long-term access to data, and much more. An active planning process must be pursued that focuses on effectively implementing the recommendations for next decade as well as sustaining and building the knowledge and information system beyond the next decade.

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 the knowledge and information system for the next decade and beyond.

The training of future scientists who are needed to interpret observations, and who will turn the measurements into knowledge and information is exceedingly important in the framework of this report. To ensure that effective and productive use of these data is maximized, resources must be dedicated toward an education and training program that spans a broad range of communities. A robust program to train users on the use of these observations will result in a wide range of societal benefits ranging from improved weather forecasts to more effective emergency management to better land-use planning.

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.

Observations from Space: History, Promise, and Reality (Executive Summary), National Academy Press, Washington, D.C., 1995.

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Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond

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

Space Studies Board
Division on Engineering and Physical Sciences

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[1]Term ended January 2006.
[2]The committee notes with deep regret Aram Mika's death on May 18, 2005.

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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 the National Aeronautics and Space Administration (NASA) Office of Earth Science, the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite Data and Information Service, and the U.S. Geological Survey (USGS) Geography Division to conduct a decadal survey to generate consensus recommendations from the Earth and environmental science and applications communities regarding a systems approach to the space-based and ancillary observations[1] encompassing the research programs of NASA, the related operational programs of NOAA, and associated programs, such as Landsat, a joint initiative of USGS and NASA.

The National Research Council responded to this request by approving a study and appointing the Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future to conduct it. The committee oversaw and synthesized the work of seven thematically organized study panels.

In carrying out the study, participants endeavored to set a new agenda for Earth observations from space in which practical benefits to humankind play a role equal to that of the quest to acquire new knowledge about Earth. Those benefits range from short-term needs for information, such as weather forecasts and warnings for protection of life and property, to the longer-term scientific understanding that is necessary to enable future applications that will benefit in society in ways still to be realized.

As detailed in the study statement of task (Appendix A), the NRC was asked to:

1. Review the status of the field to assess recent progress in resolving major scientific questions outlined in relevant prior NRC, NASA, and other relevant studies and in realizing desired predictive and applications capabilities via space-based Earth observations;
2. Develop a consensus of the top-level scientific questions that should provide the focus for Earth and environmental observations in the period 2005-2015;
3. Take into account the principal federal- and state-level users of these observations and identify opportunities and challenges to the exploitation of the data generated by Earth observations from space;
4. Recommend a prioritized list of measurements, and identify potential new space-based capabilities and supporting activities within NASA ESE and NOAA NESDIS to support national needs for research and monitoring of the dynamic Earth system during the decade 2005-2015; and
5. Identify important directions that should influence planning for the decade beyond 2015.

As will be clear in reading this report, the committee devoted nearly all its attention to items 2, 3, and 4. Challenged by the breadth of the Earth sciences, the committee was not able to provide a comprehensive response to item 1, although parts of the task are addressed implicitly as the status of the field and outstanding science questions informed the recommendations for new programs. The committee

[1] Unless stated otherwise, the term "space-based observations" of Earth refers to remote-sensing measurements enabled by instruments placed on robotic spacecraft.

also did not address item 5 systematically, although many of the recommended programs extend beyond 2015 and therefore indicate directions for the decade 2015-2025.

At the request of agency sponsors and Congress, the committee prepared an interim report that was published in April 2005. *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*[2] described the national system of environmental satellites as "at risk of collapse." That judgment was based on the observed precipitous decline in funding for Earth-observation missions and the consequent cancellation, descoping, and delay of a number of critical missions and instruments.[3] A particular concern expressed in the interim report was the vitality of the field, which depends on a robust Explorer-class[4] program and a vigorous research and analysis (R&A) program to attract and train scientists and engineers and to provide opportunities to exploit new technology and apply new theoretical understanding in the pursuit of discovery and high-priority societal applications.

Those concerns have greatly increased in the period since the interim report was issued, because NASA has canceled additional missions and NOAA's polar and geostationary satellite programs have suffered major declines in planned capability. In addition to a decision not to adapt the already completed Deep Space Climate Observatory (DSCOVR) for launch,[5] NASA has canceled plans for the Hydros mission to measure soil moisture, delayed the Global Precipitation Mission (GPM) another 2.5 years,[6] and made substantial cuts in its R&A program.[7]

Instruments planned for inclusion on the National Polar-orbiting Operational Environmental Satellite System (NPOESS)[8] will play a critical role in maintaining and extending existing Earth

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

[3] Ibid, Table 3.1, p. 17.

[4] In this report, "Earth Science Explorer-class missions" refers to NASA's Earth System Science Pathfinders (ESSP) and an even less costly new class of missions, which the committee refers to as Venture class. According to NASA, the ESSP program "is characterized by relatively low to moderate cost, small to medium sized missions that are capable of being built, tested, and launched in a short time interval. These missions are capable of supporting a variety of scientific objectives related to Earth science, including the atmosphere, oceans, land surface, polar ice regions, and solid-Earth. Investigations include development and operation of remote sensing instruments and the conduct of investigations utilizing data from these instruments." See "Earth System Science Pathfinder" on the Web at http://science.hq.nasa.gov/earth-sun/science/essp.html.

[5] DSCOVR, formerly known as Triana, would have been the first Earth-observing mission to make measurements from the unique perspective of Lagrange-1 (L1), the neutral-gravity point between the Sun and Earth. DSCOVR would have a continuous view of the Sun-lit side of Earth at a distance of 1.5 million kilometers. In addition to its Earth-observing instruments, DSCOVR carries an instrument that would continue the real-time measurements of solar wind that are currently being made by instruments on the Advanced Composition Explorer (ACE) spacecraft, which has been at L1 since October 1997. The solar-wind monitor was a high-priority recommendation of the 2002 National Research Council decadal survey in solar and space physics. See National Research Council, *Review of Scientific Aspects of the NASA Triana Mission: Letter Report*, Washington, D.C.: The National Academies Press, 2000, and National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, Washington, D.C.: The National Academies Press, 2002.

[6] As the present report was being completed, survey members learned of possible changes in GPM funding that would result in even further delays. Indeed, GPM, which was assumed to be part of the approved baseline of programs on which the survey would build its recommendations, might, in fact, have to compete for funding with survey-recommended missions.

[7] Total R&A for NASA science missions was cut by about 15% in the president's 2007 budget (relative to 2005). In addition, the cuts were made retroactive to the start of the current fiscal year. Over the last 6 years, NASA R&A for the Earth sciences has declined in real dollars by some 30 percent.

[8] Since the early 1960s, the United States has maintained two distinct polar weather and environmental monitoring satellite programs, one for military use and one for civilian use. While data from both programs were exchanged, each program operated independently. In 1994, after a multi-year review concluded that civilian and military requirements could be satisfied by a single polar satellite program, President Clinton directed the merger of the two programs into one—NPOESS. The program is managed by the triagency Integrated Program Office (IPO),

measurements. In 2006, NPOESS underwent a recertification process that resulted in a substantial diminution of its originally planned capabilities.[9] In addition to a substantial increase in program costs (to at least $3.7 billion), delay in the first scheduled launch from 2010 to 2013, and reduction (from six to four) in the number of spacecraft that will be procured, the descoped NPOESS program provides only "core" sensors related to the primary mission of NPOESS, which is weather forecasting. "Secondary" sensors that would provide crucial continuity to some long-term climate records and other sensors that would have provided new data are not funded by NOAA in the new NPOESS program.[10]

Plans to make the Landsat spacecraft "operational" by including a land-imaging sensor on NPOESS have also been abandoned. For over 30 years, Landsat observations have provided the best means of examining the relationship between human activities and their terrestrial environment. NASA plans to develop a continuity mission for Landsat (Landsat Data Continuity Mission, LDCM); however, gaps in the Landsat record appear inevitable, and whether there will be an LDCM follow-on is unclear.

The sponsors of this study, the first NRC decadal survey in the Earth sciences, requested a report that would provide an integrated program of space-based and related programs that were ordered by priority, presented in an appropriate sequence for deployment, and selected to fit within an expected resource profile during the next decade.

Execution of the survey presented several challenges, chief among them that prior to the inauguration of this decadal survey the Earth science community had no tradition of coming together to build a consensus toward research priorities that cross conventional disciplinary boundaries. Geologists, oceanographers, atmospheric scientists, ecologists, hydrologists, and others rarely view themselves as part of a continuum of Earth scientists bound by common goals and complementary programs. It was the need to create a broad community perspective where none had existed before that was a particular challenge to this decadal survey. Furthermore, the breadth and diversity of interests of the Earth science communities required priority-setting among quite different scientific disciplines. That heterogeneity required a multidisciplinary set of committee and panel members; it also required involving the broad Earth-science community from the start in defining the scope and objectives of the survey. The effort began by informing the community of the proposed study through an extensive outreach effort, including solicitation and evaluation of written comments on the proposed study. Several planning workshops were held, beginning with a major community-based workshop in August 2004 at Woods Hole, Massachusetts.

The division of responsibilities between NASA and NOAA for Earth observations from space also required the committee to consider critical interagency issues. Historically, new Earth remote sensing capabilities have been developed in a process in which NASA develops first-of-a-kind instruments that, once proved, are considered for continuation by NOAA. In particular, many measurements now being performed by instruments on NASA's Earth Observation System of spacecraft—Terra, Aqua, and Aura[11]—are planned for continuation on the NOAA-Department of Defense next generation of polar-orbiting weather satellites, NPOESS. Problems in managing the "transition" of NASA-developed spacecraft and instruments to NOAA have been the subject of several NRC studies.[12]

A related issue concerns the process for extension of a NASA-developed Earth-science mission that has accomplished its initial objectives or exceeded its design life. NASA decisions on extension of operations for astronomy, space science, and planetary exploration are based on an analysis of the incremental cost versus anticipated *science* benefits. Historically, NASA has viewed extended-phase

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using personnel of the Department of Commerce, Department of Defense, and NASA. See http://www.ipo.noaa.gov/.

[9] House Committee on Science, "The Future of NPOESS: Results of the Nunn-McCurdy Review of NOAA's Weather Satellite Program," June 8, 2006.

[10] "Impacts of NPOESS Nunn-McCurdy Certification on Climate Research," White Paper Prepared for OSTP by Earth Science Division, Science Mission Directorate, NASA. Draft August 15, 2006, 44pp.

[11] See "The Earth Observing System," a Web page maintained by the NASA Goddard Space Flight Center, at <http://eospso.gsfc.nasa.gov/>.

[12] See in particular National Research Council, *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations*, Washington, D.C.: The National Academies Press, 2003.

operations for Earth-science missions as "operational" and therefore the purview of NOAA. However, the compelling need for measurements in support of human health and safety and for documenting, forecasting, and mitigating changes on Earth creates a continuum between science and applications—illustrating again the necessity for multiple agencies to be involved intimately in the development of Earth science and applications from space.[13]

Previous NRC decadal-survey committees in astronomy and astrophysics, planetary exploration, and solar and space physics were able to draw on NASA-sponsored community-generated "roadmaps" of high-priority near-term and longer-term missions and programs that would advance the field.[14] In the absence of such roadmaps, the present survey began its work by soliciting concept proposals from the community. The committee issued a request for information (RFI) in early 2005 and received over 100 thoughtful responses (the RFI is shown in Appendix D; responses are summarized in Appendix E). The responses were studied by members of the panels and helped to inform decisions regarding the recommended missions and associated programs.

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.[15] Similarly, the committee could not fully digest the ramifications of changes in the GOES-R program of NOAA,[16] and it was in no position to consider the implications of possible large-scale reduction in funding and later delay of the GPM. 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.

Given the breadth of the Earth sciences, there were multiple ways to organize the present study. Organizers of the study considered a discipline-based structure focused on the atmosphere, ocean, land, cryosphere, and solid Earth. However, an important deficiency of that approach was its potential to de-

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[13] National Research Council, *Extending the Effective Lifetimes of Earth Observing Research Missions*, Washington, D.C.: The National Academies Press, 2005.

[14] NASA did complete an Earth Science and Applications from Space Strategic Roadmap in 2005. However, that effort began after this decadal survey had been inaugurated, and the effort was truncated soon after the change in NASA administration in April 2005. Survey activities were well under way when the roadmap was completed in the middle of 2005.

[15] For example, a key instrument on all six originally planned NPOESS spacecraft was the Conical Scanning Microwave Imager/Sounder (CMIS). CMIS was to collect global microwave radiometry and sounding data to produce microwave imagery and other meteorologic and oceanographic data. Data types included atmospheric temperature and moisture profiles, clouds, sea surface winds, and all-weather land and water surfaces. CMIS contributed to 23 of the NPOESS "environmental data records" (EDRs) and was the primary instrument for nine EDRs. CMIS was terminated in the certified NPOESS program, and a smaller and less technically challenging instrument is planned as its replacement. The detailed specifications of the replacement have not been announced. Similarly, the mitigation plan for the altimeter, ALT, which was removed from the NPOESS C-3 and C-6 spacecraft, is also unknown at this time.

[16] Plans to develop the next generation of operational sounder from geostationary orbit, the Hyperspectral Environmental Suite (HES), were terminated in late August 2006. HES, scheduled for launch in 2013, was a key sensor on the GOES-R series, NOAA's next generation of geostationary environmental spacecraft. It was to provide high-spectral-resolution radiances for numerical-weather-prediction (NWP) applications and temperature and moisture soundings (and various derived parameters) for a host of applications dealing with near-term or short-term predictions. See, for example, Timothy J. Schmit, Jun Li, and James Gurka, "Introduction of the Hyperspectral Environmental Suite (HES) on GOES-R and Beyond," presented at the International (A)TOVS Science Conference (ITSC-13) in Sainte Adele, Quebec, Canada, October 18-November 4, 2003. Available at http://cimss.ssec.wisc.edu/itwg/itsc/itsc13/proceedings/session10/10_9_schmit.pdf#search=%22hes%20goes-r%22.

emphasize the interdisciplinary interactions of Earth as a system as they pertain to forcing, feedback, prediction, products, and services. After considerable discussion at the Woods Hole 2004 meeting, it was decided that the survey's panels should be more thematic; therefore, the study was organized with a committee overseeing the work of seven thematically organized study panels. The panels focused on

1. Earth-science applications and societal needs.
2. Land-use change, ecosystem dynamics, and biodiversity.
3. Weather (including space weather[17] and chemical weather[18]).
4. Climate variability and change.
5. Water resources and the global hydrologic cycle.
6. Human health and security.
7. Solid-Earth hazards, resources, and dynamics.

Given that structure, such disciplines as oceanography and atmospheric chemistry, although not visible in the title of a given panel, influenced the priorities of multiple panels. For example, oceanography was a key discipline represented in all the panels. Similarly, atmospheric chemistry was an important driver in deliberations among several panels, including those on human health and security; land-use change, ecosystem dynamics, and biodiversity; climate variability and change; and weather. Moreover, NASA and NOAA have taken a similar interdisciplinary approach in their strategic planning; hence, this structure was thought to be of greater use for NASA's and NOAA's implementation plans. Nevertheless, there was concern in parts of the community that some sciences and applications might not be adequately addressed by the panel structure.

Each panels met three times during the course of the study. In several instances, panels also met jointly with other panels or with the committee. The committee met in whole or in part some 10 times during the study. Community outreach efforts included presentations and "town hall" sessions at professional meetings, including those of the American Geophysical Union and the American Meteorological Society; study updates posted to various newsletters; articles in professional journals; and the creation of a public Web site. As noted above, members of the community were invited to submit ideas to advance Earth science and applications from space. Briefings were also given on many occasions to various NRC committees. Finally, numerous members of the community communicated directly with survey participants. Community input was particularly helpful in the final stages of the study to ensure that essential observational needs of disciplines would be met by the interdisciplinary mission concepts of the panels.

The final set of program priorities and other recommendations was established by consensus at a committee meeting at Irvine, California, in May 2006, and in later exchanges by telephone and e-mail. The committee's final set of priorities and recommendations does not include all the recommendations made by the study panels, although it is consistent with them. As described in Chapter 2, panels used a common template in establishing priority lists of proposed missions. Because execution of even a small portion of the missions on the panels' lists was not considered affordable, panels worked with committee members to develop synergistic mission "rollups" that would maximize science and application returns across the panels while keeping within a more affordable budget. Frequently, the recommended missions represented a compromise in an instrument or spacecraft characteristic (including orbit) between what two or more panels would have recommended individually without a budget constraint.

[17] The term *space weather* refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and that can affect human life and health.

[18] There is no single definition of *chemical weather*, but the term refers to the state of the atmosphere as described by its chemical composition, particularly important variable trace constituents such as ozone, oxides of nitrogen, and carbon monoxide. Chemical weather has a direct impact in a number of areas of interest for this study, especially air quality and human health.

All the recommendations offered by the panels merit support—indeed, the panels' short lists of recommendations were culled from the over 100 RFI responses and other submissions—but the committee took as its charge the provision of a strategy for a strong, balanced national program in Earth science for the next decade that could be carried out with what are thought to be realistic resources. Difficult choices were inevitable, but the recommendations presented in this report reflect the committee's best judgment, informed by the work of the panels and discussions with the scientific community, about which programs are most important for developing and sustaining the Earth-science enterprise.

The process that resulted in the final set of recommendations and the usual procedures imposed by the NRC guards against the potential for anyone to affect report recommendations unduly. The vetting process for nominees to an NRC committee ensured that all survey members declared any conflicts of interest. The size and expertise of the committee served as a further check on individual biases or conflicts in that each member of the committee had an equal "vote." The consensus-building process by which each panel produced short priority lists of missions and then a final set of "rollup" missions ensured further vetting of the merits of each candidate mission by the entire committee. The committee, whose collective expertise spanned the relevant disciplines for this survey, then had the final say in reviewing and approving the overall survey recommendations.

On June 13, 2006, after a full House Committee on Science hearing on the recertification of NPOESS, Representative Sherwood Boehlert, chair of the House committee, sent a letter to Michael Griffin, administrator of NASA, requesting that the NRC decadal survey undertake additional tasks to "analyze the impact of the loss of the climate sensors, to prioritize the need for those lost sensors, and to review the best options for flying these sensors in the future." NASA later sent the NRC a request to

> 1. Analyze the impact of the changes to the NPOESS program, which were announced in June 2006…The analysis should include discussions related to continuity of existing measurements and development of new research and operational capabilities.
> 2. Develop a strategy to mitigate the impact of the changes described [in the item above]. . . . Included in this assessment will be an analysis of the capabilities of the portfolio of missions recommended in the decadal strategy to recover these capabilities, especially those related to research on Earth's climate. . . . The committee should provide a preliminary assessment of the risks, benefits, and costs of placing—either on NPOESS or on other platforms—alternative sensors to those planned for NPOESS. Finally, the committee will consider the advantages and disadvantages of relying on capabilities that may be developed by our European and Japanese partners.

The present report provides a preliminary analysis of item 1 (see, in particular, Chapter 9, the report of the Panel on Climate Variability and Change; also see Table 2.5). Most of the tasks in item 2 will be performed by a new panel, which will be formed in early 2007 and will deliver a short report later in 2007 (see Table 2.5 for a summary of the impact of NPOESS instrument cancellations and descopes).

Finally, the survey co-chairs and the study director wish to acknowledge the extraordinary contributions to this report from Randy Friedl, a member of the Panel on Earth Science Applications and Societal Needs. Dr. Friedl was unsparing of his time and offered wise counsel at several critical stages in the development of this report. He and his Jet Propulsion Laboratory colleague, Stacey W. Boland, provided invaluable assistance in synthesizing the work of the survey study panels, obtaining budget information, creating graphs, and critiquing large portions of Part I of this report.

Acknowledgment of Reviewers

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

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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 Marcia McNutt, Monterey Bay Aquarium Research Institute and Richard Goody, Harvard University (emeritus professor). Appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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