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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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

NATIONAL RESEARCH COUNCIL
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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

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[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.

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[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:

Antonio J. Busalacchi, Jr., University of Maryland,
Dudley B. Chelton, Jr., Oregon State University,
John R. Christy, University of Alabama,
Timothy L. Killeen, National Center for Atmospheric Research,
Uriel D. Kitron, College of Veterinary Medicine, University of Illinois at Urbana-Champaign,
David M. Legler, U.S. CLIVAR Office,
Pamela A. Matson, Stanford University,
M. Patrick McCormick, Hampton University,
John H. McElroy, University of Texas at Arlington,
R. Keith Raney, Johns Hopkins University, Applied Physics Laboratory,
William J. Shuttleworth, University of Arizona,
Norman H. Sleep, Stanford University,
Sean C. Solomon, Carnegie Institution of Washington,
David T. Sandwell, Scripps Institution of Oceanography,
Carl I. Wunsch, Massachusetts Institute of Technology,
James A. Yoder, Woods Hole Oceanographic Institution, and
A. Thomas Young, Lockheed Martin Corporation (retired).

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.

Contents

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

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[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:

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[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.

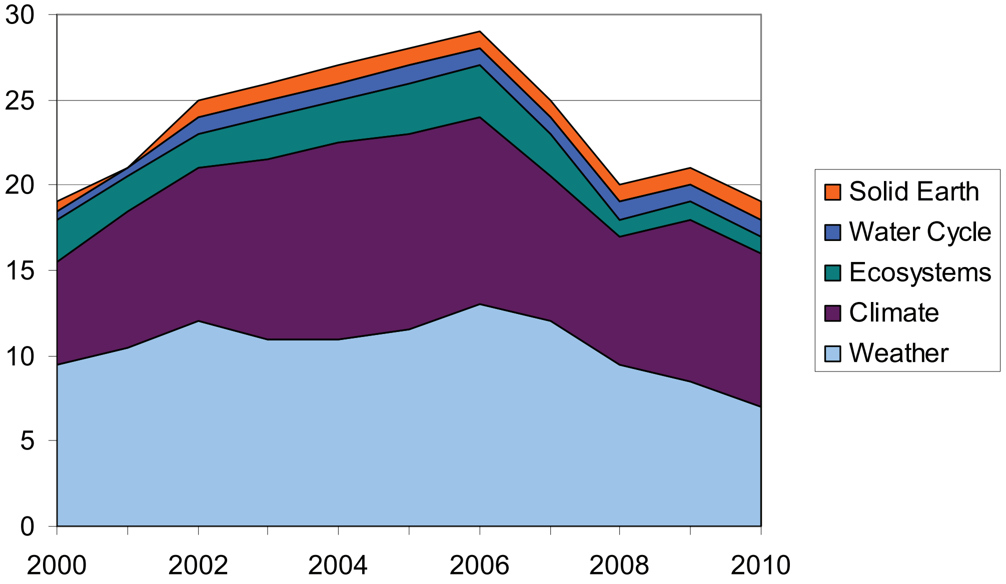

FIGURE ES.1a Number of U.S. space-based Earth Observations missions in the current decade. An emphasis on climate and weather is evident, as is the decline in number of missions near the end of the decade. For the period from 2007 to 2010, missions were generally assumed to operate for four years past 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.

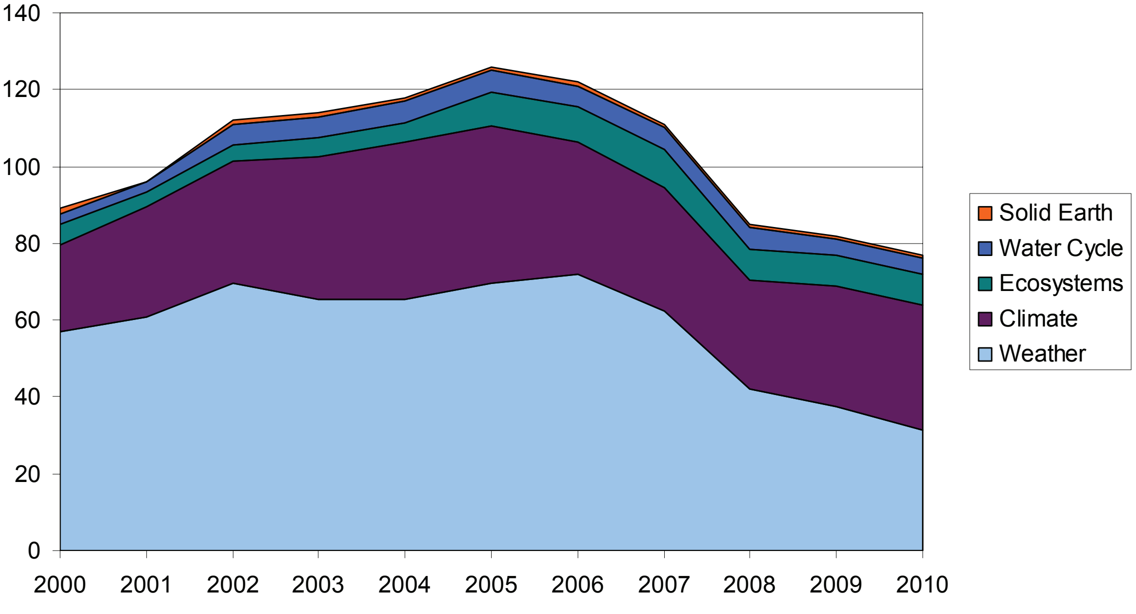

FIGURE ES.1b Number of U.S. space-based Earth Observations instruments in the current decade. Emphasis on climate and weather is evident as is the decline in number of instruments near the end of the decade. For the period from 2007 to 2010, missions were generally assumed to operate for four years past 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:*[7] NOAA should restore several key climate, environmental, and weather observation capabilities to its planned NPOESS and GOES-R[8] missions; namely:**

- **Passive measurements of ocean vector winds and all-weather sea-surface temperatures descoped from the 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.[9]**

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)[10] 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.**
- **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 vertical-resolution measurements of temperature and water vapor from geosynchronous orbit 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:

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[7] Inaccurate wording of this four-part recommendation in the initially released prepublication copy of this report was subsequently corrected by the committee to reflect its intent to recommend a capability for ensuring continuity of the ongoing record of measurements of total solar irradiance and of Earth's radiation budget. As explained in the description of the CLARREO mission in Chapter 4, the committee recommends that the CERES Earth radiation budget instrument and a total solar irradiance sensor be flown on the NPP satellite and that these instruments or their equivalent be carried on the NPOESS spacecraft or another suitable platform.

[8] 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 time frame to December 2014.

[9] Without this capability, no national or international ozone-profiling capability will exist after the EOS Aura mission ends in 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.

[10] The NASA-managed NPOESS Preparatory Project (NPP), a joint mission involving NASA and the NPOESS Integrated Program Office (IPO), has a twofold purpose: (1) to provide continuity for a selected set of calibrated observations with the existing Earth Observing System measurements for Earth science research and (2) to provide risk reduction for four of the key sensors that will fly on NPOESS, as well as the command and data-handling system. The earliest launch set for NPP is now September 2009, a delay of nearly 3 years from the plans that existed prior to the 2006 Nunn-McCurdy certification. See <http://jointmission.gsfc.nasa.gov/> and <http://www.nasa.gov/pdf/150011main_NASA_Testimony_for_NPOESS-FINAL.pdf>.

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 that such approaches will both strengthen 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 expansion and contraction of economies, and the intensification of agriculture.

Both of these concerns have been highlighted in the scientific and policy literature;[11] 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.

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[11] 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 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.

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[12] 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.[13] 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.**

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[12] One mission, CLARREO, has two components – a NASA component and a separate NOAA component.

[13] 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.

- **NASA should implement a set of 15 missions 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 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 and Earth 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 large 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.[14]

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."**[15]

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

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[14] 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.

[15] 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.[16] To this end, the committee makes the following recommendations:

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[16] 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.

Part I:

An Integrated Strategy for Earth Science and Applications from Space

1

Earth Science: Scientific Discovery and Societal Applications

SETTING THE DECADAL VISION

> 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]

These declarations, first made in the committee's Interim Report, are the foundation of the committee's "decadal vision" of a program of Earth-science research and applications in support of society—a vision that includes advances in fundamental understanding of Earth 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 from space in which practical benefits to humankind play an equal role with the quest to acquire new knowledge about the Earth.

The Interim Report described how satellite observations have been critical to scientific efforts to understand the Earth as a system of connected components, including the land, oceans, atmosphere, biosphere, and solid-Earth. It also gave examples of how these observations have served the nation, helping to save lives and protect property, strengthening national security, and contributing to the growth of our economy[2] through provision of timely environmental information. However, the Interim Report also identified a substantial risk to the continued availability of these observations, warning that the nation's system of environmental satellites was "at risk of collapse." In the short period since the publication of the Interim Report, budgetary constraints and programmatic difficulties at NASA and NOAA have greatly exacerbated this concern (see Preface). At a time of unprecedented need, the nation's Earth observation satellite programs, once the envy of the world, are in disarray.

The precipitous decline of the nation's present and planned research and operational Earth satellite programs has implications that extend from the vitality of the research and engineering "pipeline" to many aspects of the U.S. economy. Indeed, a greater scientific understanding of the coupled Earth system, and the translation of this understanding into useful information and predictions, is essential for sustained stewardship of our natural resources, which are vital to national economic growth and improved environmental quality. In a 2006 report, the authors of a World Bank study argue that in addition to our traditional understanding of physical and human capital as sources of wealth, so, too, should exhaustible and renewable natural resources be measured, accounted for, and stewarded as a large and significant source of a nation's wealth. The Bank's analysis shows that just as sound investments in physical and human capital underlie economic growth and prosperity, so, too, do nations that most effectively manage

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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] It has been estimated that one third of the $10 trillion U.S. economy is weather-sensitive or environment-sensitive (NRC, *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations*, The National Academies Press, Washington, D.C., 2003.).

their natural resources evidence a quantitatively significant economic edge—these nations are indeed demonstratively wealthier.[3]

SIDEBAR 1.1 LESSONS LEARNED FROM KATRINA

FIGURE 1.1.1 Hurricane Katrina at 1700 U.T.C., Sunday August 28, 2006. Image from MODIS on NASA's Terra spacecraft. SOURCE: NOAA, "Billion Dollar U.S. Weather Disasters," available at http://www.ncdc.noaa.gov/oa/reports/billionz.html.

The earthquake and tsunami that devastated large swaths of coastal South and East Asia on December 26, 2004, and the hurricanes that struck the Gulf Coast of the United States in 2005, are stark examples of the vulnerability of human society to natural disasters and the importance of observations and warning systems. Hurricane Katrina, which resulted in the deaths of more than 2,000 people, and is estimated to have caused some $125 billion in damages,[1] was one of the worst disasters in U.S. history. Further, the financial costs of Katrina do not account for other "costs" to society, including the impacts on the families of survivors and the likely permanent loss of large swaths of New Orleans. The impact of natural disasters, and the need for observations that can improve predictions and warnings, will only grow as society becomes more complex and as populations and economic infrastructure increase in vulnerable geographical and ecological areas.

The committee draws several important lessons from the Katrina disaster. The committee notes that forecasts three days in advance of Hurricane Katrina's landfall in the Gulf, which were based on mathematical models that ingested space- and aircraft-based observations, proved highly accurate. These forecasts were heeded by most people in affected areas, and likely saved thousands of lives. The accuracy of predictions of the track for Katrina demonstrates the power of using a large number of different observations of the Earth system in computer models to make accurate and life-saving forecasts. However, while forecasts for the hurricane track were unusually accurate, forecasts related to the magnitude and location of the storm surge were less so, indicating the need for enhanced research and better observations (NSB, 2006). Like the tsunami of December 2004, the tragic aftermath of Katrina also illustrated the necessity to have a response system in place to take full advantage of disaster warnings (EOS, 2005).

The investments in Earth science and applications that are recommended in this report are needed to restore important capabilities that have been lost and to build capacity for an Earth information system that will be increasingly important in the decades to come. Fundamental improvement is needed in the structure and function of the nation's observation and information systems to inform policy choices about economic prosperity and security, protect human health and property, and judiciously manage the resources of the planet. It is essential that the observation and information systems be viewed as an

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[3] World Bank, *Where is the Wealth of Nations?: Measuring Capital for the 21st Century*, World Bank, Washington, D.C., 2006.

important element of a linked system, extending from observations to services for our public and private communities. These communities—at the federal, state, and local levels, and the private sector — have come to trust that this system will develop and use the best available scientific understanding and provide critical information in a timely manner.

To achieve the Decadal Vision, the committee makes the following overarching recommendation:

The United States government, working in concert with the private sector, academia, the public, and our 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 apply more effectively new knowledge in pursuit of societal benefits.*

In concert with these actions, the nation should execute a *strong, intellectually-driven Earth sciences program* and an integrated *in situ* and space-based observing system. Improved understanding of the coupled Earth system and global observations of the Earth are linked components that are the foundation of an effective Earth Information System. Developing this system will require an expanded observing system, which in turn is tied to a larger global observing system of the kind envisioned in the Global Earth Observation System of Systems (GEOSS), a program initiated by the United States.[4] It will also require tools such as computer models to assimilate the observations and extract useful information as well make predictions; and information technology to disseminate data to user communities. The *mission component* of this observational system is the primary focus of this report and is summarized in Chapter 2 and detailed in Part II.

EARTH SYSTEM SCIENCE AND APPLICATIONS—BUILDING UPON A SUCCESSFUL PARADIGM

> We live today in what may appropriately be called the "Anthropocene"—a new geologic epoch in which humankind has emerged as a globally significant—and potentially intelligent—force capable of reshaping the face of the planet
>
> —Crutzen (2002)

The development of "Earth system science," recognizes that changes to the Earth result from interactions among its components: the atmosphere, hydrosphere, biosphere, and lithosphere, as well as human activities. The complex interactions among the Earth system components give rise to the need for a systems approach to understanding the linkages, dependencies, and interactions among the components.[5] The unique capabilities of space-based observations are proving to be essential in understanding the complexities and interactions among Earth system components. Applications flow

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[4] More than 60 countries, the European Commission, and more than 40 international organizations are supporting a U.S.-led effort to develop a global Earth Observation System. See, "47 Countries, European Commission Agree to Take Pulse of the Planet: Milestone Summit Launches Plan to Revolutionize Understanding of How Earth Works," available at http://www.noaanews.noaa.gov/stories2004/s2214.htm.

[5] The Earth system science concept promotes the study of Earth as an integrated system of atmosphere, ocean, and land, while bridging the traditional disciplines of physics, chemistry, and biology. The field of Earth science has matured from the point of understanding processes in ocean, land, and atmosphere components treated separately to studying their connections at global scales. See <http://eospso.gsfc.nasa.gov/eos_homepage/for_educators/eos_edu_pack/p01.php> and references therein. See also, "What is Earth System Science?," available at <http://www.usra.edu/esse/essonline/whatis.html>.

from these observations and understanding; for example, the demonstrated and substantial improvements in weather prediction are largely attributable to improved scientific understanding derived from the interpretation of satellite observations and the use of the observations themselves in weather prediction models (Hollingsworth et al., 2005). Likewise, satellite observations have played a key role in:

- The discovery, understanding, and monitoring of the depletion of stratospheric ozone.
- Understanding the transport of air pollution between countries and continents.
- Determining the rates of glacial and sea ice retreat.
- Monitoring land-use change due to both human and natural causes.
- Monitoring and understanding changing weather patterns due to land-use change and aerosols.
- Determining changes in strain and stress through the earthquake cycle.
- Understanding the global-scale effects of El Niño and La Niña on weather patterns and ocean productivity.
- Forecasting the development and tracking hurricanes, typhoons, and other severe storms.
- Assessing damage from natural disasters and targeting relief.

To achieve the committee's vision, it is necessary to build upon the paradigm of Earth system science and strengthen its dual role—science and applications—to produce the benefits that society demands. While this duality has always been an element of Earth information, it must be leveraged in a more effective way than in the past. Efforts over the past decade and longer have been focused on building an understanding of how the Earth functions as a system. Today, only a limited portion of this knowledge is applied directly in the service of society.

The world is facing 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 significant changes in climate. These changes are occurring over and above the stresses imposed by the natural variability of a dynamic planet, as well as the effects of past and existing patterns of conflict, poverty, disease, and malnutrition. Further, these changes interact with each other and with natural variability in complex ways that cascade through the environment across local, regional, and global scales. Addressing these environmental challenges will not be possible without enhanced collaboration of Earth scientists with researchers from other disciplines, including the social, behavioral, and economic sciences and policy experts.

In summary, the committee's vision of understanding the Earth as one of the greatest intellectual challenges facing humanity *and* applying this understanding to benefit society and ensure its health, prosperity, safety, and sustainability, can be realized only through a robust, integrated, and flexible system of observations and models, which are then applied to pressing short- and long-term social problems. Observations of all parts of the Earth system fuel scientific discovery of how the only planet known to support life has evolved over the past and will change in the future. The observations also support a wide variety of applications for the benefit of society. As the complexity and vulnerability of society increases, the value of Earth observations and information becomes greater than ever. Thus, the tasks of sustaining, strengthening and extending current observational capabilities and other vital parts of the Earth Information System to meet the growing socio-economic needs and opportunities provide the motivation for this report and the rationale for its conclusions.

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

It is to these new and needed observations to which we turn in the next chapter.

SIDEBAR 1.2 ESTABLISHING THE GROUNDWORK FOR TODAY

Beginning with Lyell's[6] work on the slow time scales of geological change, and continuing with Wegener's[7] and Hess'[8] theories on continental drift and sea floor spreading, Earth scientists uncovered many of the mysteries of plate tectonics. Bort's[9] discovery of a layered atmosphere and the calculations of Arrhenius'[10] and Milankovitch[11] concerning CO_2-induced warming and ice age cooling allowed us to understand the basic workings of the atmosphere and mechanisms that determine Earth's climate. These advances have enabled society to build the early foundation of understanding that has resulted now in the ability to evaluate and plan for earthquake and volcanic hazards, to accurately forecast the weather, to explain much about past climates, and to begin predicting future climate change.

SIDEBAR 1.3 AN ABUNDANCE OF CHALLENGES

Improving Weather Forecasts. Testing and systematically improving forecasts of weather with respect to meteorological, chemical, and radiative change places unprecedented demands on technical innovation, computational capacity, and developments in assimilation and modeling that are required for effective and timely decision and response structures. While weather forecasting has set in place the clearest and most effective example of the operational structure required, future progress depends in very important ways on a renewed emphasis on innovation and strategic investment for weather forecasting in its broader context. The U.S. has lost leadership to the Europeans in the international arena in an array of pivotal capabilities ranging from medium range weather forecasting to long-term climate forecasting. Without leadership in these and other forecasting capabilities, we lose economic competitiveness.

Protecting Against Solid-Earth Hazards. Whether hazards such as earthquakes and tsunamis, volcanic eruptions, and landslides have consequences that are only serious or are truly catastrophic depends on whether or not they have been anticipated and preparations have been made to mitigate their effects. Yet mitigation is expensive, available resources are limited, and decisions must be made on how to prioritize these expenditures. At present, the solid Earth science required for decision-making is hampered by lack of data– a situation perhaps analogous to trying to make reliable weather forecasts before global

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[6] Sir Charles Lyell (1797-1875), author of *Principles of Geology* and considered to be the founder of modern geology (http://www.mnsu.edu/emuseum/information/biography/klmno/lyell_charles.html).

[7] Alfred Wegener (1880-1930), German climatologist and geophysicist and author of *The Origins of Continents and Oceans*, suggested the revolutionary idea of continental drift and plate tectonics (http://www.mnsu.edu/emuseum/information/biography/klmno/lyell_charles.html).

[8] Harry Hammond Hess (1906-1969), professor of geology at Princeton University, influential in setting the stage for the emerging plate-tectonics theory in the early 1960s. Hess believed in many of the observations Wegener used in defending his theory of continental drift, but he had different views about large-scale movements of the Earth (http://pubs.usgs.gov/gip/dynamic/HHH.html).

[9] Léon Teisserenc de Bort (1855-1913), French meteorologist who discovered the stratosphere (http://en.wikipedia.org/wiki/L%C3%A9on_Teisserenc_de_Bort).

[10] Svante Arrhenius (1859-1927), Swedish chemist, first formulated the idea that changes in the levels of carbon dioxide in the atmosphere could substantially alter the surface temperature through the greenhouse effect. In its original form, Arrhenius' greenhouse law reads as follows: *if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression.* (http://en.wikipedia.org/wiki/Svante_Arrhenius).

[11] The Serbian astrophysicist Milutin Milankovitch is best known for developing one of the most significant theories relating Earth motions and long-term climate change. Now known as the Milankovitch Theory, it states that as the Earth travels through space around the sun, cyclical variations in three elements of Earth-sun geometry combine to produce variations in the amount of solar energy that reaches Earth. (http://earthobservatory.nasa.gov/Library/Giants/Milankovitch/).

observations were available. We know the total rates of deformation across fault systems, but lack the information to determine reliably which faults are most likely to rupture, let alone when these ruptures will occur. Volcanic eruptions and landslides often have precursors, but our ability to detect and interpret these precursors is severely limited by lack of observations.

Ensuring Our Water Resources. The nation's water supply is of paramount importance to public health, stability, and security in the industrial and agricultural sectors, and prosperity in vast reaches of rural America. Yet our ability to obtain key observations, to test forecasts of intermediate and long-term change, and to establish a coherent protocol for adaptation to large variations that are intrinsic to the hydrologic cycle is inadequate. The Western United States is the most rapidly developing region of the country and is also the most vulnerable in terms of water supply. According to statistics compiled by the USDA/NOAA-sponsored Drought Monitor, the past decade, the driest since the 1950s, has had the greatest impacts in states including Oklahoma, New Mexico, Texas, and Colorado. In early 2005, Lake Powell was at its lowest level since the reservoir was constructed in the 1960s. Why this drought occurred, how long it will continue, and how future droughts may be affected by a warming climate are questions whose answers have profound implications for both the United States and the world.

Maintaining Healthy and Productive Oceans. A warming ocean raises sea level, alters precipitation patterns, may cause stronger storms, and may accelerate the melting of sea ice and glaciers. The increased acidity of our oceans due to rising CO_2 levels portends dramatic adverse impacts for ocean biological productivity. These changes will be critical for all, but none more so than for those living in coastal regions. Over the last few decades a concerted effort to develop satellite measurements of the ocean has revolutionized our understanding of ocean circulation, air-sea interaction, and ocean productivity. Just as we are poised to make major contributions to climate predictions on times scales of seasons to decades, and to monitor the changes in the ocean's health, we are in danger of losing many of our ocean satellite observations because of programmatic failures and/or a lack of a will to sustain the measurements.

Mitigating Adverse Impacts Of Climate Change. It is now well-understood that changes in the physical climate system over the last century have been driven in a significant part by human activities, and that the human influence on climate is increasing. Future climate changes may be much more dramatic and dangerous. For example, rising sea levels will increase coastal flooding during storms, which may become more intense. Effective mitigation of dangerous future climate change and adaptation to changes that are certain to occur even with mitigation efforts requires knowing how the climate is changing and why it is changing. But we do not have a well-developed climate monitoring system, and fundamental changes are needed in the U.S. climate observing program. We do not have, nor are there clear plans to develop, a long-term global benchmark record of critical climate variables that are accurate over very long time periods, can be tested for systematic errors by future generations, are unaffected by interruption, and are pinned to international standards. Difficult climate research questions also remain; for example, the cloud/water feedback in climate models. Another example concerns the geographic distribution of the land- and ocean-sources and sinks of carbon dioxide. These sources and sinks do not simply map with geography, but rather display complex patterns and interactions. As nations seek to develop strategies to manage their carbon emissions and sequestration, the capacity to quantify the present-day *regional* carbon sources and sinks does not exist.

Protecting Our Ecosystems. Nearly half of the land surface has been transformed by direct human action, with significant consequences for biodiversity, nutrient cycling, soil structure and biology, and climate. The beneficial effects of these transformations—additions to the food supply, improved quality of human habitat and in some cases ecosystem management, large-scale transportation networks, and increases in the efficiency of movement of goods and services—have also been accompanied by deleterious effects. More than one-fifth of terrestrial ecosystems have been converted into permanent croplands; more than one-quarter of the world's forests have been cleared; wetlands have shrunk by one-half, and most of the temperate old growth forest has been cut. More nitrogen is now fixed synthetically and applied as fertilizers in agriculture than is fixed naturally in all terrestrial ecosystems, and far too much of this nitrogen runs off the ground and ends up in the coastal zone. Coastal habitats are also being dramatically altered; for example, 50 percent of the world's mangrove forests, important tropical coastal habitats existing at the interface between land and sea, and coastal buffers from wave action, have been removed.[12] That the world's marine fisheries are either overexploited or, for certain fish, already depleted, is well known; one recent study even suggests the potential for their total collapse by the middle of this century.[13] And yet, we do not have adequate spatially-resolved estimates of the planet's biomass and primary production, and how it is changing and interacting with climate variability and change.

Improving Human Health. Environmental factors have strong influences on a broad range of human health effects including infectious diseases, skin cancers, or chronic and acute illnesses resulting from contamination of air, food, and water. Public health decision-making has benefited from the continued availability of satellite-derived data on land-use, land cover, oceans, weather, climate, and atmospheric pollutants. However, the stresses of global environmental change and growing rates of resource consumption now place greater demands for collection and analyses of data that describe how environmental factors relate to patterns of morbidity and mortality. Further improvements in the application of remote sensing technologies will allow for better understanding of disease risk and prediction of disease outbreaks, more rapid detection of environmental changes that affect human health, identification of spatial variability in environmental health risk, targeted interventions to reduce vulnerability to health risks, and enhanced knowledge of human health-environment interactions.

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[12] Elise Granek, "Effects of mangrove removal on algal growth: Biotic and abiotic changes with potential implications for adjacent coral patch reefs," Abstract, Contributed Oral Session 83: Human Impacts on Coastal Areas, 2005 meeting of the Ecological Society of America (ESA), Montreal Canada.

[13] Boris Worm, et. al., "Impacts of Biodiversity Loss on Ocean Ecosystem Services," *Science* 314(3):787-790, 2006.

2
The Next Decade of Earth Observations from Space

The first chapter of this report presents the committee's vision for an Earth information system that will be commensurate with national needs. In this chapter, the committee describes the observational portion of a strategy for obtaining an integrated set of space-based measurements in the next decade—one that will extend our ability to address increasingly urgent issues that are facing our planet.

The committee recognizes that space-based measurements are but one part of the requisite Earth information and knowledge system; however, the space-based measurements provide unique and key data for analyzing Earth as a global system of interconnected human and natural processes. Together with the development of a resilient and effective Earth information system, the recommended observations will strengthen the relationship between the global Earth system science framework and the decision-maker framework to address emerging regional and global challenges. These include:

- ***Ice sheets and sea level.*** 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?
- ***Large-scale and persistent shifts in precipitation and water availability.*** Will droughts become more widespread in the western US, 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?
- ***Transcontinental air pollution.*** 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?
- ***Shifts in ecosystem structure and function in response to climate change.*** 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?
- ***Human health and climate change.*** 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" (see Sidebar 2.1) that could result from a cooling of the stratosphere, which would be associated with climate change?
- ***Extreme events, including severe storms, heat waves, earthquakes and volcanic eruptions.*** Will tropical cyclones and heat waves become more frequent and more intense? Are major fault systems nearing release of stress via strong earthquakes?

While past investments in Earth remote sensing have provided spectacular advances in particular areas, such as in the accuracy of weather predictions, the above list of challenges highlights the class of new, integrated questions that are being asked by the public and policymakers as they seek to understand new risks and vulnerabilities of a rapidly-evolving Earth system. Naturally, new issues and questions will emerge from continued system-level study of the Earth. The next twenty years must bring a new level of integration of our understanding of the Earth system components.

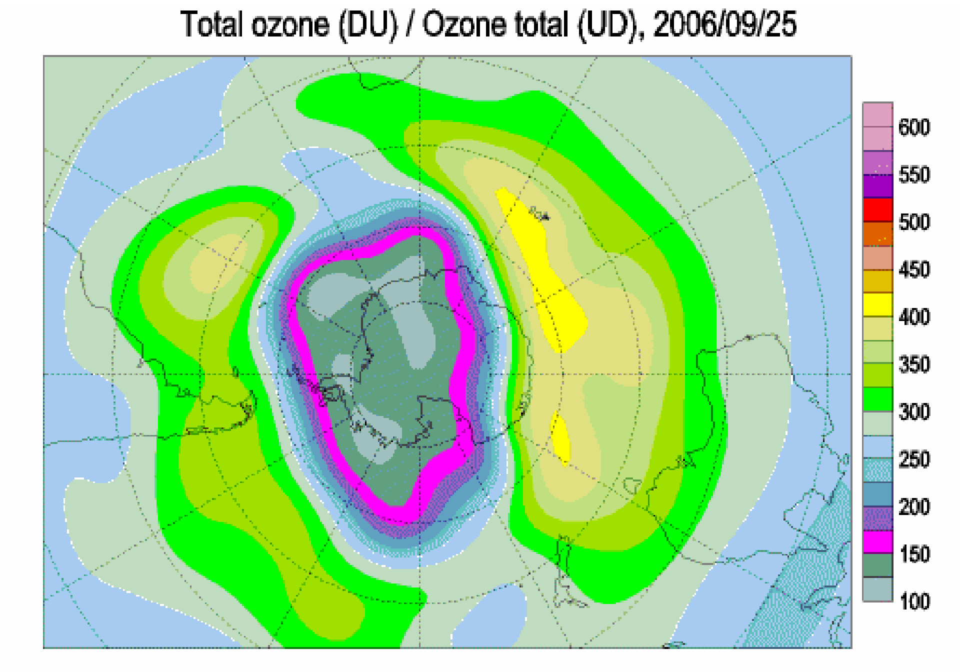

FIGURE 2.1 The 2006 hole in the Antarctic ozone layer was the most serious on record, exceeding that of 2000. Not only was it the largest in surface area (matching 2000), but it also suffered the most mass deficit, meaning that there was less ozone over the Antarctic than ever previously measured. SOURCE: NASA and ESA satellite data (http://www.theozonehole.com/ozonehole2006.htm).

The observational plan presented here represents a distillation of many key measurements across the range of interplaying societal and Earth science themes into a core set of space-borne missions. This set carries a great potential for major advances in scientific understanding as well as substantial benefits to many of the key societal challenge areas (see Figure 2.2). The committee recommends a plan that has a well-defined and justified set of missions providing critical new observations and data for addressing emerging societal issues. The plan builds upon lessons learned from the development and use of the current fleet of space-based instruments.

The committee's recommended list of missions focuses on what are considered to be the highest priority observational needs. To avoid potential technical and cost problems with overly ambitious missions, the plan limits the instrument set on any planned mission to one that can deliver clear synergies between observations. In time, it may also prove necessary to consider alternative institutional arrangements for executing these inherently multi-discipline, multi-agency missions. In particular, as the plans of other space-faring nations and organizations crystallize, their contributions to meeting observational needs will need to be carefully evaluated. In the next section, we articulate the key elements of the current Earth observing system that are essential components of next decade's system.

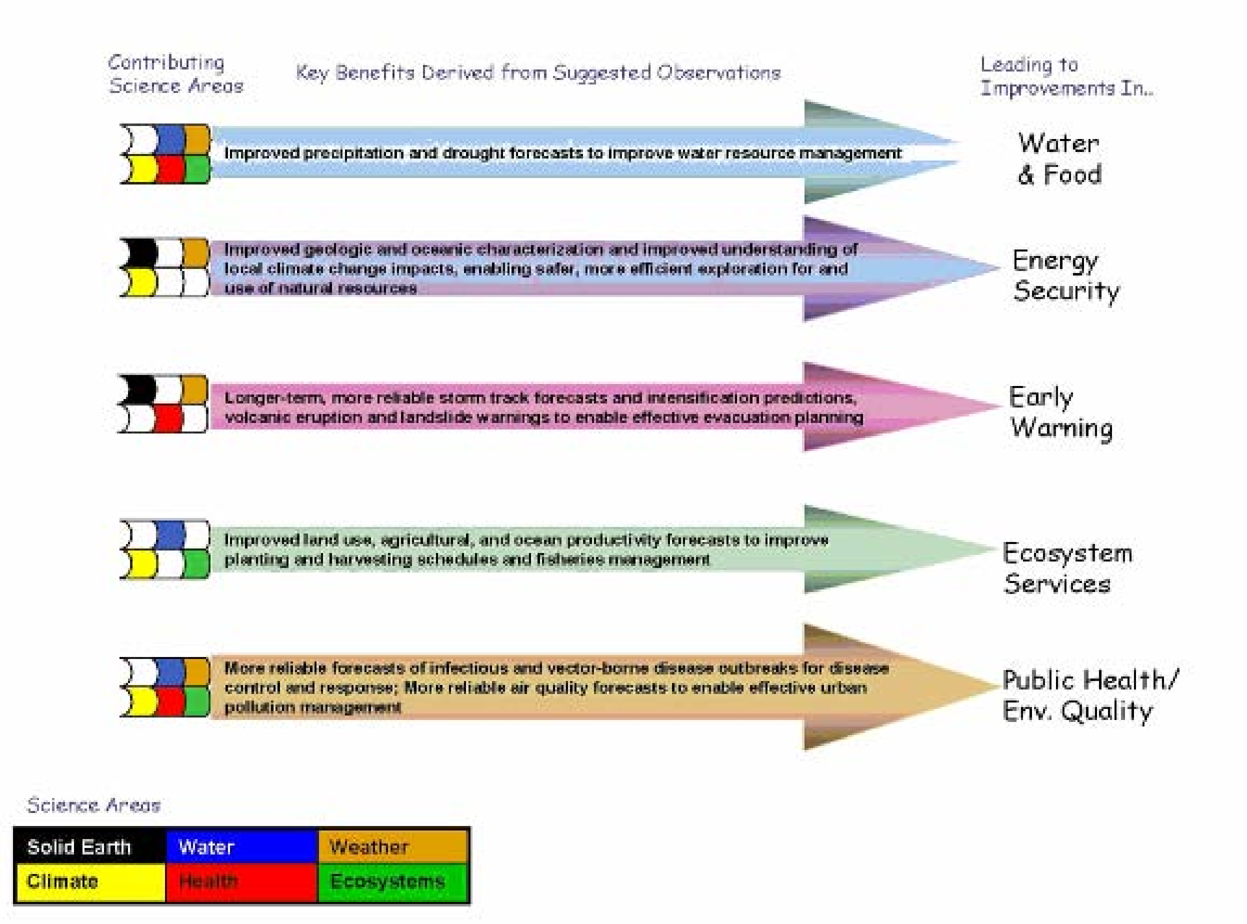

FIGURE 2.2 Addressing any given societal challenge requires scientific progress in many Earth system areas as shown in these examples. Colored squares represent the scientific themes that contribute substantially to each of the selected benefit areas.

SETTING THE FOUNDATION: OBSERVATIONS IN THE CURRENT DECADE

Over the past forty years, the U.S. civilian agencies have built an increasingly capable space-based Earth observing system. NOAA has continued to deploy and maintain an operational system of weather satellites and expand the utility of these observations (see Box 2.1). In 2004, NASA completed deployment of its ambitious Earth Observing System (EOS) research fleet that consists of three multi-instrumented spacecraft (i.e. Terra, Aqua, and Aura) designed to characterize most of the major Earth system components. NASA also complemented EOS with several smaller, more focused missions, and instruments (on international partner spacecraft) that extended capability in the areas of weather and climate. In addition, USGS and NASA have continued their collaboration on ecosystem science and related societal benefit areas through the Landsat mission series. The result of these efforts has been a steadily increasing number of space-based observations that stands at the current level of 29 operating spacecraft and 122 instruments (including both U.S. missions and international missions with U.S.

instruments) [for lists of missions and instruments, see CEOS (2002)]. Unfortunately, we are at the high-water mark in observing capability unless we alter course immediately (see Figures 2.3a and 2.3b).

The extensive scientific and societal contributions of the NOAA/NASA/USGS satellite observing capabilities are evidenced by the thousands of scientific publications and applications of the data for environmental forecasts. This record of accomplishment has already been set forth in Chapter One, and numerous additional examples will be found in Part III of this Report. As noted in Chapter 1, perhaps the largest impact of space-based observations to date has been on weather forecasting and the many societal benefits stemming from such improved forecasts (Hollingsworth et al., 2005). One need only take note of the National Weather Service's current practice of providing 10-day weather forecasts to recognize the scientific gains that have been made in the last decade.

Space-based observations have also figured prominently in climate research (NRC, 2004). Factors that drive climate change are usefully separated into forcings and feedbacks. A *climate forcing* is an energy imbalance imposed on the climate system either externally or by human activities. Examples include changes in solar energy output, volcanic emissions, deliberate land modification, or anthropogenic emissions of greenhouse gases, aerosols, and their precursors. A *climate feedback* is an internal climate process that amplifies or dampens the climate response to a specific forcing. An example is the increase in atmospheric water vapor that is triggered by warming due to rising carbon dioxide (CO_2) concentrations, which acts to further amplify the warming because of the greenhouse properties of water vapor.

Observations of key climate forcings and feedbacks, diagnostics (e.g., temperature, sea level), and the consequences of climate change (e.g., sea ice decrease) have helped identify potentially dangerous changes in Earth's climate. These observations have catalyzed climate research and enabled significant improvements in climate models. In fact, these improvements have brought into existence a class of *Earth System Models*[1] that couple atmosphere, ocean, land, and cryosphere systems. These models not only provide better estimates of spatially- and temporally-resolved patterns of climate change but also provide the basis for addressing other environmental challenges such as changes in biogeochemical cycles of carbon and nitrogen and the impacts of these changes now and in the future (see Sidebar 2.2).

Despite these advances, this extraordinary foundation of global observations is in decline. Between 2006 and the end of the decade, the number of operating sensors and instruments will likely decrease by around 40 percent, given that most satellites in NASA's current fleet are *well past* their nominal lifetimes. Furthermore, the replacement sensors on NPOESS, when they exist, are generally less capable than their EOS counterparts. This decreased quantity of space-borne assets will persist into the early part of next decade (see again Figures 2.3a and 2.3b).

Partly causing and certainly amplifying this observational collapse of space-based measurements is the decline in NASA's Earth Science budget. Between the years 2000 and 2006, this part of NASA's budget decreased over 30 percent when adjusted for inflation (see Figure 2.5a). This reduction, if it persists, translates to approximately $4 billion less to develop Earth science missions over the next decade. For example, a $4 billion reduction might translate into some 8-12 fewer space-based research missions and perhaps $1 billion less for associated research and analysis.

The NASA/NOAA Earth Observation Satellite system, launched at the turn of the millennium, is aging and the existing plan for the future is entirely inadequate to meet the coming challenges. The NOAA budget has been growing (see Figure 2.5b), but this growth is now swamped by the large cost overruns in the NPOESS program. It also appears likely that the GOES-R program will also experience cost growth.[2] Completing even the descoped NPOESS program will require several billion dollars of

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[1] For example, GFDL and NCAR (www.cgd.ucar.edu/research/models/ccsm.html) Earth System Models.

[2] See testimony of the Under Secretary for Oceans and Atmosphere VADM Conrad C. Lautenbacher, USN (Ret) before the House Science Committee (Chairman Sherwood Boehlert, R-NY), on GAO GOES-R report, September 29, 2006. Available at http://www.legislative.noaa.gov/Testimony/lautenbacher092906.pdf.

funding beyond that planned as recently as December 2005.[3] Thus, NPOESS represents a major lien on future budgets; one that is so great that the agency's capability to provide observations in support of climate research or other non-"core" missions will be severely compromised.

BOX 2.1 EMERGING APPLICATIONS USING POES AND GOES OPERATIONAL MEASUREMENTS

In addition to its primary role in weather forecasting, NOAA has been working with other agencies and institutions to create operational data products for other societal benefit areas. Examples of these products include:

Fire Detection. Monitoring wildfires is a difficult task in many parts of the world with high levels of biological diversity in remote locations. The Center for Applied Biodiversity (CABS) at Conservation International, with the University of Maryland, uses data from the MODIS Rapid Response System[1] to provide an e-mail alert system warning of fires near or in protected areas. The service is available by way of a no-cost subscription.[2] For the past 10 years the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin - Madison has used the GOES series of satellites to monitor fires and smoke in the Western Hemisphere. Multi-spectral GOES-8 imagery (visible, 3.9 10.7, and 12 microns) is used to identify and catalogue fire activity in South America associated with deforestation, grassland management, and agriculture. This has yielded the Automated Biomass Burning Algorithm (ABBA).[3] In 2002, NOAA's Satellite Products and Services Review Board approved the transition from preoperational to operational status of the Wildfire Automated Biomass Burning Algorithm (WF-ABBA) data product.

Air Quality Monitoring. AirNOW is a government program involving EPA, NOAA, NASA, NPS, the news media, and tribal, state, and local agencies (http://airnow.gov). The program reports conditions for ozone and particulate pollution to provide the public with easy access to daily air quality index (AQI) forecasts and real time AQI conditions for over 300 cities. USA Today is an AirNOW partner as well. UMBC operates an air quality web site, "The Smog Blog,"[4] with daily posts and NASA satellite images, EPA data, etc. There have been over 3,000,000 hits over 2 years, ~ 15,000 visits per month, with ~800 unique visitors per week including EPA, NASA, NOAA, and the states.

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[1] See <http://maps.geog.umd.edu/>.
[2] See "Fire Alert Fact Sheet."
[3] See <cimss.ssec.wisc.edu/goes/burn/detection.html>.
[4] See <alg.umbc.edu/usaq>.

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[3] See testimony of the Under Secretary for Oceans and Atmosphere VADM Conrad C. Lautenbacher, Jr., USN (Ret.) before the House Science Committee (Chairman Sherwood Boehlert, R-NY), on the results of the Nunn-McCurdy Certification Review of the National Polar-orbiting Operational Environmental Satellite System (NPOESS), June 8, 2006. Available at http://www.legislative.noaa.gov/Testimony/lautenbacher060806.pdf.

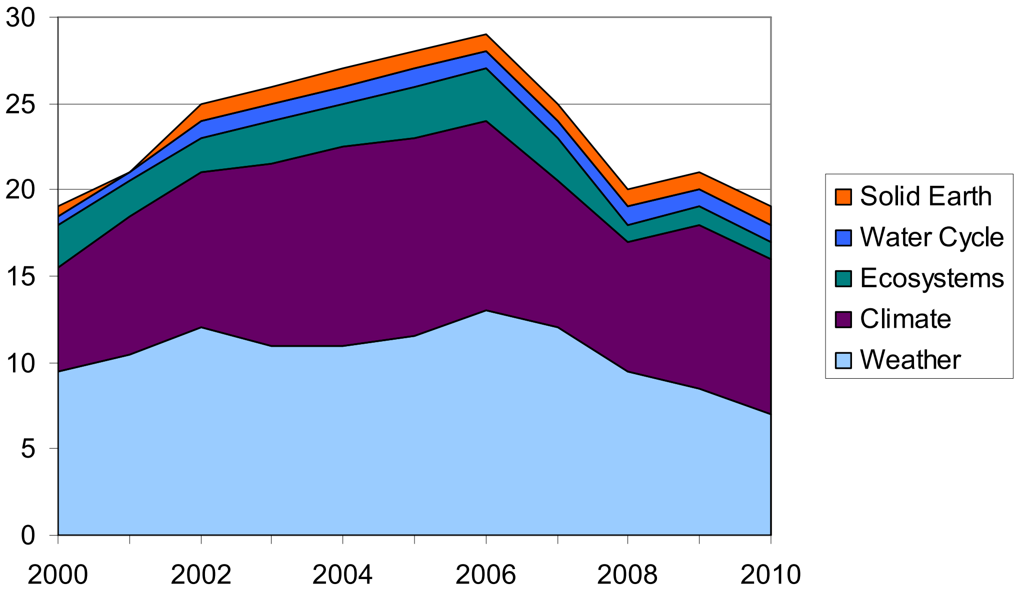


FIGURE 2.3a Number of U.S. space-based Earth Observations missions in the current decade. Emphasis on climate and weather is evident, as is the decline in number of missions near the end of the decade. SOURCE: NASA and NOAA websites for mission durations. For the period from 2007 to 2010, missions were 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.

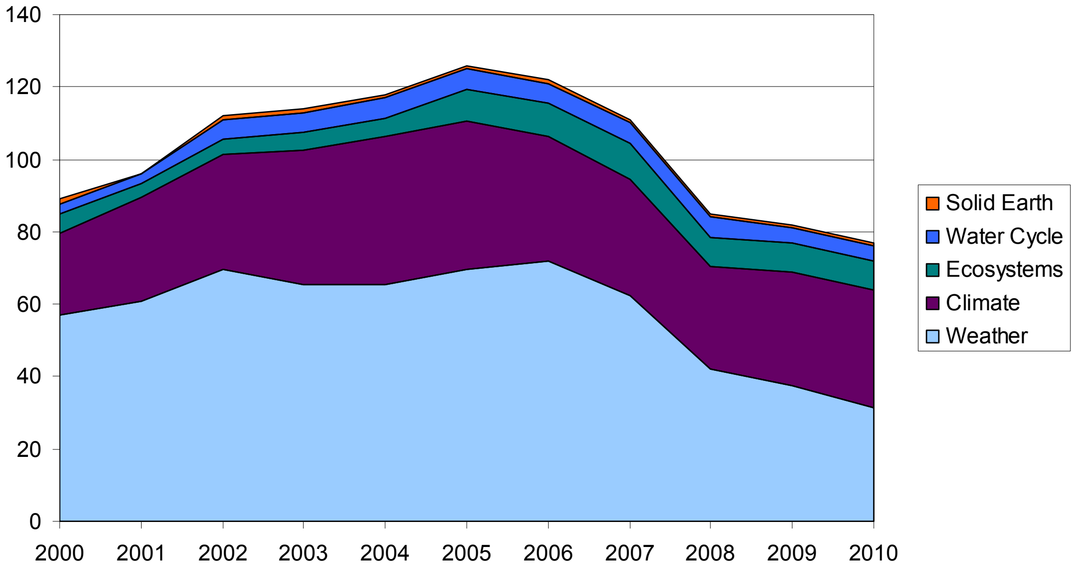
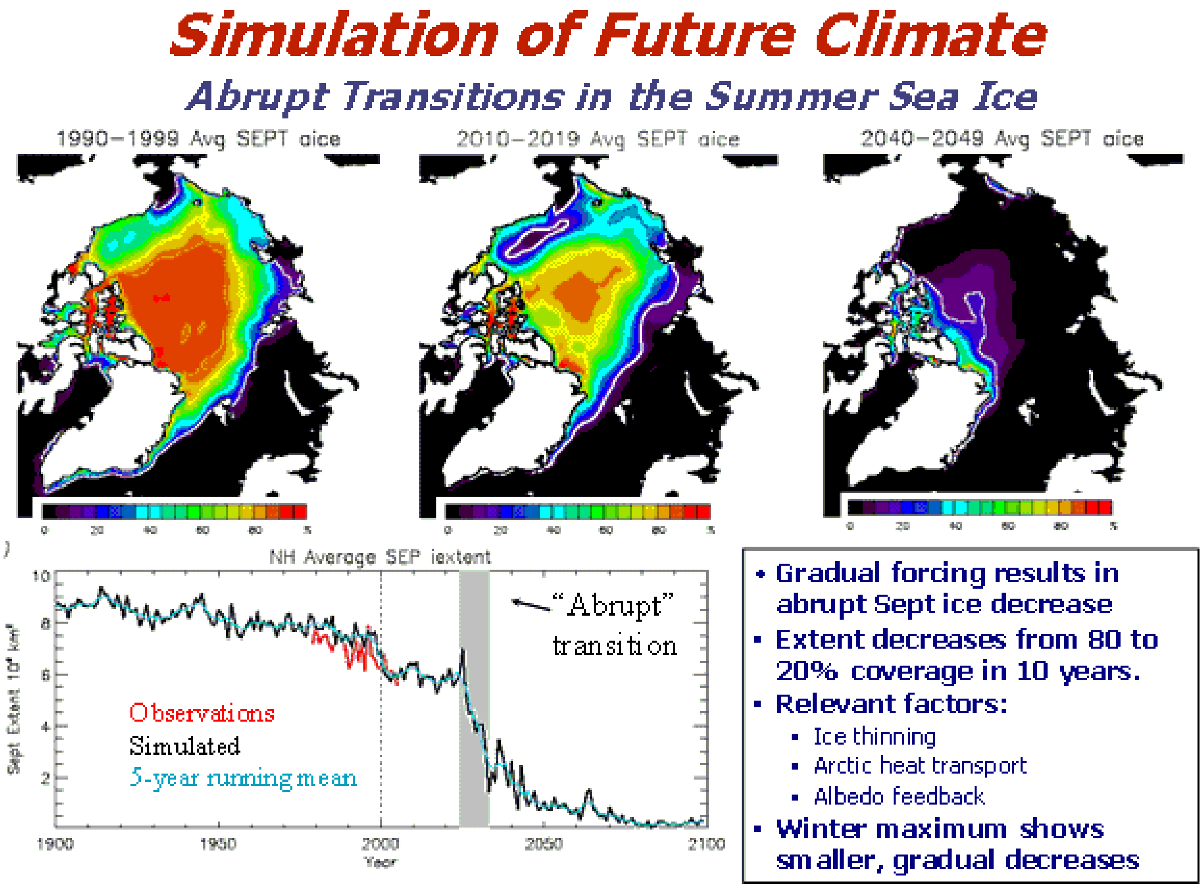


FIGURE 2.3b Number of U.S. space-based Earth Observations instruments in the current decade. Emphasis on climate and weather is evident as is the decline in number of instruments near the end of the decade. SOURCE: Information from NASA and NOAA websites for mission durations. For the period from 2007 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.

SIDEBAR 2.2

Future IPCC scenario runs with NCAR's CCSM3 show abrupt transitions in the September sea ice cover. In the most dramatic event, shown here, the ice cover goes from conditions similar to observed in the 1990s to essentially September ice-free conditions in a decade. This is driven by a number of factors: the thinning of the ice cover to a more vulnerable state, increases in Arctic ocean heat transport which possibly trigger the event, and the albedo feedback which accelerates the ice retreat.



- Gradual forcing results in abrupt Sept ice decrease
- Extent decreases from 80 to 20% coverage in 10 years.
- Relevant factors:
  - Ice thinning
  - Arctic heat transport
  - Albedo feedback
- Winter maximum shows smaller, gradual decreases

FIGURE 2.4

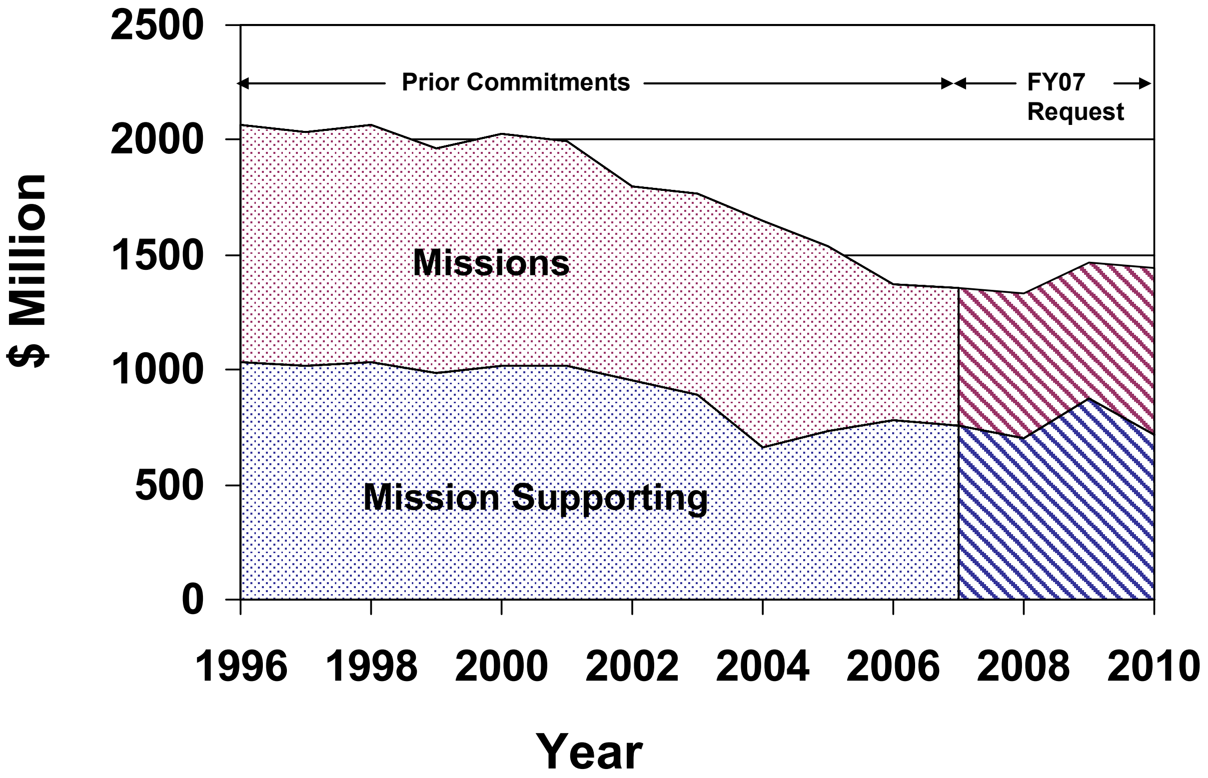


FIGURE 2.5a The NASA budget for Earth science research and application demonstrations for the period 1996 to 2010 (in fixed 2006-year dollars).

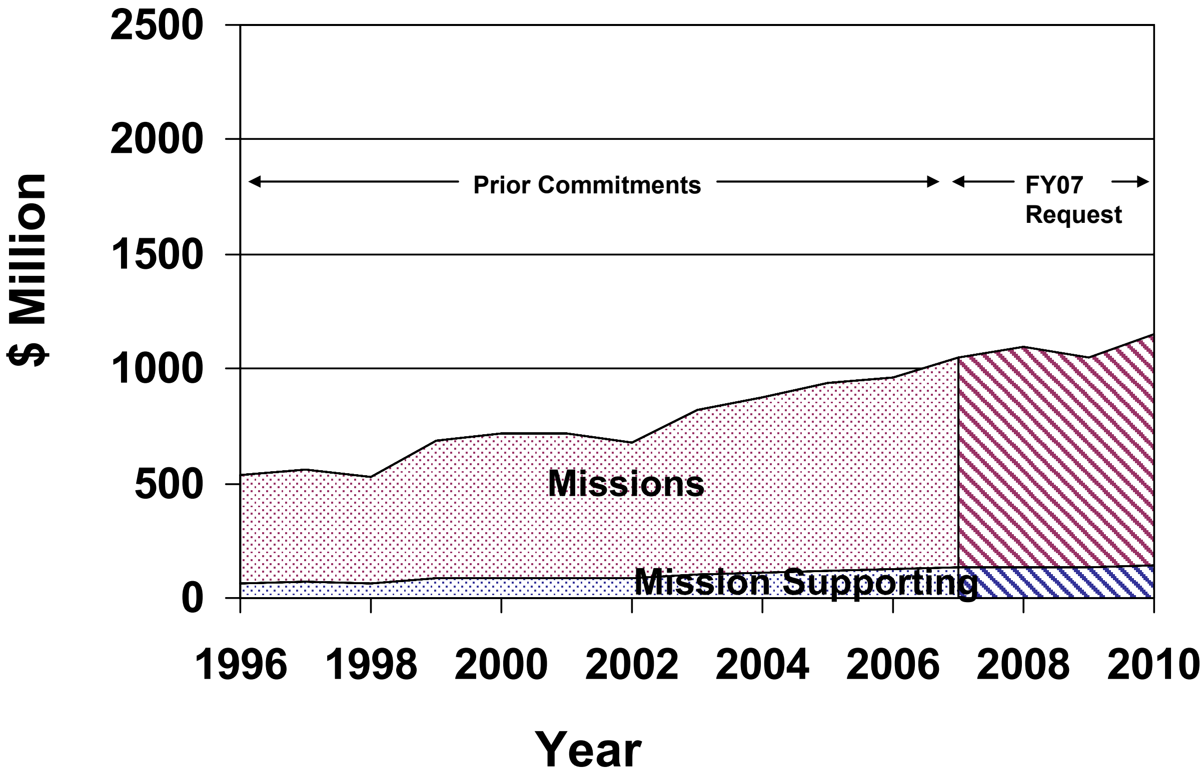


FIGURE 2.5b: The NOAA NESDIS budget for Earth applications and research for the period 1996 to 2010 (in fixed 2006-year dollars).

Among the many missions expected to cease over the next few years, the committee has identified several for NOAA and NASA 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. For NOAA, there are many observational capabilities that need to be restored to NPOESS, but this topic must be considered against a reexamination of the logic, costs, and benefits of the current (September 2006) NPOESS and GOES-R plan. The reexamination of NPOESS and GOES-R will be conducted by a subsequent NRC "fast-track" study to be conducted and concluded in 2007.

The present committee's analysis of the implications of NPOESS instrument descopes and cancellations is hampered by the absence of information about changes to key sensors. In particular, the CMIS (Conical Microwave Imager/Sounder) instrument on NPOESS, which was to provide continuity of records of sea surface temperature and sea ice—time-series critical to global climate studies—has been canceled, and the specifications for its replacement, MIS (Microwave Imager/Sounder), are not yet known.[4] Similarly, the mitigation plan for the now de-manifested altimeter, ALT, is not yet known.

There are, however, several measurements whose continuity is of sufficient importance to either climate research, ozone monitoring, or operational weather systems to deserve immediate attention. For climate these include total solar irradiance and Earth radiation. For ozone these include ozone limb sounding capability in addition to total solar irradiance. For weather, these include sea surface vector winds and temperature and water vapor soundings from geostationary and polar orbits. As detailed in the committee's Interim Report, the substitution of passive microwave sensor data for active scatterometry data would worsen El Niño and hurricane forecasts and weather forecasts in coastal areas.[5] Nevertheless, given the precarious status of existing surface wind measurements,[6] it is imperative that a measurement capability, such as the one on MetOp, be available to prevent a data gap when the NASA QuikSCAT mission terminates.

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[4] CMIS was also to provide measurement of sea-surface vector winds and all-weather profiles of atmospheric temperature and humidity. It also had important capabilities for measurement of soil moisture and precipitation. See "NPOESS ERA Microwave Imager," Presentation at a NOAA conference in Silver Spring, MD, on October 26, 2006, which is available on the world wide web at: <http://www.ipo.noaa.gov/polarmax/2006/day03/5.5Kunkee_20061001_PolarMax_MIS_v2.ppt>.

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

[6] Interim Report, pp. 19-20.

Recommendation:[7] **NOAA should restore several key climate, environmental, and weather observation capabilities to its planned NPOESS and GOES-R[8] missions; namely:**

- **Passive measurements of ocean vector winds and all-weather sea-surface temperatures descoped from the 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.[9]**

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)[10] 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.**
- **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 vertical-resolution measurements of temperature and water vapor from geosynchronous orbit 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.**

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[7] Inaccurate wording of this four-part recommendation in the initially released prepublication copy of this report was subsequently corrected by the committee to reflect its intent to recommend a capability for ensuring continuity of the ongoing record of measurements of total solar irradiance and of Earth's radiation budget. As explained in the description of the CLARREO mission in Chapter 4, the committee recommends that the CERES Earth radiation budget instrument and a total solar irradiance sensor be flown on the NPP satellite and that these instruments or their equivalent be carried on the NPOESS spacecraft or another suitable platform.

[8] 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 time frame to December 2014.

[9] Without this capability, no national or international ozone-profiling capability will exist after the EOS Aura mission ends in 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.

[10] The NASA-managed NPOESS Preparatory Project (NPP), a joint mission involving NASA and the NPOESS Integrated Program Office (IPO), has a twofold purpose: (1) to provide continuity for a selected set of calibrated observations with the existing Earth Observing System measurements for Earth science research and (2) to provide risk reduction for four of the key sensors that will fly on NPOESS, as well as the command and data-handling system. The earliest launch set for NPP is now September 2009, a delay of nearly 3 years from the plans that existed prior to the 2006 Nunn-McCurdy certification. See <http://jointmission.gsfc.nasa.gov/> and <http://www.nasa.gov/pdf/150011main_NASA_Testimony_for_NPOESS-FINAL.pdf>.

The committee believes such a process will strengthen both the technological foundation of GEO-based soundings and provide the requisite experience for efficient operational implementation of GEO-based soundings. We also note that this issue will be studied in more detail as part of the NRC "fast-track" study, which is scheduled to begin in early 2007.

Finally, while there are many concerns over the NASA out-year budget, two topics deserve particular mention. One is changing global precipitation patterns resulting from changing climate. The other is changing patterns of land use due to the needs of a growing population, the expanding and contracting of economies, and intensification of agriculture. Both of these concerns have been highlighted in the scientific and policy literature (e.g., IPCC, 2001 and Millennium Report, 2000) and were addressed in the 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 by measurements from instruments on the Landsat series of spacecraft.

Recommendation: NASA should continue sustained measurements of precipitation and land cover by:

- **Launching GPM on 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.

By maintaining sustained measurements of these key climate and weather variables, the nation will be in good position to achieve the committee's vision for Earth information in the next decade. The observational system that will help deliver that vision is described in the next section.

NEW OBSERVATIONS FOR THE NEXT DECADE

The prioritized set of missions forms the core recommendation of this report. In establishing this set of missions, the committee recognized that a successful program is more than the sum of its parts. The 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 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.

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[11] recommended missions (Tables 2.1 and 2.2), comprised of small (<$300 million), medium ($300 to $600 million), and large ($600 to $900 million) cost missions, phased appropriately over the next decade. Larger facility-class (>$1 billion) missions are not recommended. The missions and their specifications are given in Table 2.3.[12] As part of this strategy:

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[11] One mission, CLARREO, has two components—a NASA component and a separate NOAA component.

[12] Tables 2-1 and 2-2 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

- **NOAA should transition three research observations to operations, as recommended in Table 2.1. 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 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 2.2.**

The primary work in developing the above decadal observing strategy took place within the Survey's science panels. The panels were created around major societal issues, namely, Climate, Water Resources, Ecosystem Health, Human Health, Solid-Earth Hazards, and Weather. This categorization is quite similar to the organizing structure used in the GEOSS process. The panels first prioritized candidate observations/missions by applying the *prioritization criteria* listed in Table 2.3 to a wide range of space-based measurement approaches and mission concepts. Recommendations from previous community-based reports such as the WMO were considered (e.g. GCOS 2003, 2004, 2006a, 2006b; WMO, 2005). The complete set of high priority observations/missions identified by the panels numbered approximately 35, down substantially from the over 100 possible missions suggested in the responses to NRC's Request for Information and numerous other mission possibilities raised by individual panel members. The assessment and subsequent prioritization were based on an overall analysis by panel members as to how well each mission satisfies the criteria and the top-level community objectives (see Table 2.4). The panel reports in Part III document this analysis.

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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.

TABLE 2.1 Launch, orbit, and instrument specifications for the recommended NOAA missions. Shade colors denote mission cost categories as estimated by the NRC ESAS committee (see Box 2-2). 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 (NOAA portion)	Solar and Earth radiation characteristics for understanding climate forcing	LEO, SSO	Broadband radiometer	$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 2.2 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.

TABLE 2.3 The eight prioritization criteria used by the panels to create relative rankings of missions. Note that these are guidelines; they are not in priority order, and they may not reflect all of the criteria considered by the panels.

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

TABLE 2.4 Mapping of how the recommended missions contribute to the priority science observation/mission types identified by the individual study panels as discussed in Part III.

Recommended Mission	Mission/Observation Type Recommended by Individual Panel	Panel
CLARREO	Radiance Calibration Ozone Processes	Climate Health
GPSRO	Radiance Calibration Ozone Processes Cold Seasons Radio Occultation	Climate Health Water Weather
SMAP	Heat Stress and Drought Algal Blooms and Water-Borne Infectious Disease Vector-Borne and Zoonotic Disease Soil Moisture and Freeze/Thaw State Surface Water and Ocean Topography	Health Health Health Water Water
ICESat-II	Clouds, Aerosols, Ice and Carbon Ecosystem Structure and Biomass Sea Ice Thickness, Glacier Surface Elevation, Glacier Velocity	Climate Ecosystem Water
DESDynI	Ice Dynamics Ecosystem Structure and Biomass Heat Stress and Drought Vector-Borne and Zoonotic Disease Surface Deformation Sea Ice Thickness, Glacier Surface Elevation, Glacier Velocity	Climate Ecosystem Health Health Solid-Earth Water
XOVWM	Ocean Circulation, Heat Storage, and Climate Forcing	Climate
HyspIRI	Ecosystem Function Heat Stress and Drought Vector-Borne and Zoonotic Disease Surface Composition and Thermal Properties	Ecosystem Health Health Solid-Earth
ASCENDS	Carbon Budget Ozone Processes	Ecosystem Health
SWOT	Ocean Circulation, Heat Storage, and Climate Forcing Algal Blooms and Water-Borne Infectious Disease Vector-Borne and Zoonotic Disease Surface Water and Ocean Topography	Climate Health Health Water
GEO-CAPE	Global Ecosystem Dynamics Ozone Processes Heat Stress and Drought Acute Toxic Pollution Releases Air Pollution Algal Blooms and Water-Borne Infectious Disease Inland and Coastal Water Quality Tropospheric Aerosol Characterization Tropospheric Ozone	Ecosystem Health Health Health Health, Weather Health Water Weather Weather

continued

TABLE 2.4 *continued*

Recommended Mission	**Mission/Observation Type Recommended by Individual Panel**	**Panel**
ACE	Clouds, Aerosols, Ice, and Carbon	Climate
	Ice Dynamics	Climate
	Global Ocean Productivity	Ecosystem
	Ozone Processes	Health
	Acute Toxic Pollution Releases	Health
	Air Pollution	Health
	Algal Blooms and Water-Borne Infectious Disease	Health
	Aerosol-Cloud Discovery	Weather
	Tropospheric Aerosol Characterization	Weather
	Tropospheric Ozone	Weather
LIST	Heat Stress and Drought	Health
	Vector-Borne and Zoonotic Disease	Health
	High Resolution Topography	Solid-Earth
PATH	Heat Stress and Drought	Health
	Algal Blooms and Water-Borne Infectious Disease	Health
	Vector-Borne and Zoonotic Disease	Health
	Cold Seasons	Water
	All Weather Temperature and Humidity Profiles	Weather
GRACE-II	Ocean Circulation, Heat Storage, and Climate Forcing	Climate
	Groundwater Storage, Ice Sheet Mass Balance, Ocean Mass	Water
SCLP	Cold Seasons	Water
3D-Winds	Water Vapor Transport	Water
	Tropospheric Winds	Weather
GACM	Global Ecosystem Dynamics	Ecosystem
	Ozone Processes	Health
	Acute Toxic Pollution Releases	Health
	Air Pollution	Health
	Cold Seasons	Water
	Tropospheric Aerosol Characterization	Weather
	Tropospheric Ozone	Weather

Development of a coherent set of recommended missions was guided by the committee's overarching recommendation given in Chapter 1. Most importantly, the committee sought to create an observing system that will *treat the Earth as a system*, improving knowledge in the current weather and climate areas of inquiry and expanding the scope of observations to more fully address other key societal issues. In developing this mission list the committee recognized the importance of several guiding principles.

- *Establish and Maintain Balance to Support System Science*. The program should seek to achieve and maintain balance in a number of thematic areas in order to support the broad range of demands on Earth information. Balance is required between types of measurements (i.e. research, sustained and operational), sizes and complexity of missions, science disciplines, and across technology maturity levels.
- *Emphasize Cross-Benefiting Observations*. Earth's highly interrelated processes imply that Earth knowledge must be built largely through understanding how these processes interact with each other. Our observational system must reflect the need for cross-benefiting and interdisciplinary observations characterized by measurements across a wide range of space, time, and spectral characteristics.
- *Gain Leverage*. Resources of the many partners and related efforts, from other agencies to international programs to the private sector,[13] should be leveraged to the greatest extent possible to achieve the most comprehensive observing system possible within the available national resources.

To develop 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 fairly mature forecast tools, such as weather forecast models, the need for routine sea surface wind observations[14] by relatively mature instrument techniques set the phasing needed to provide continuity between the current QuikSCAT instrument, the planned CMIS replacement instrument on NPOESS, and the Extended Ocean Vector Winds Measurement recommended by the committee. Continuous observations of this type, with a clear operational use, are recommended to NOAA for implementation. For less mature tools, 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.

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[13] For example, as this report went to press, the committee learned of a potential partnership between NOAA and a private company that, pending support from NASA, might allow the DSCOVR spacecraft to launch on an expendable launch vehicle to L-1. In addition to its observing the Earth from a unique perspective, DSCOVR carries a solar wind monitor that would fulfill the highest space weather recommendation of the Panel on Weather as well as the highest recommendation for NOAA as expressed in the recent NRC decadal survey in solar and space physics. See, 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.

[14] See, for example, 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..

In setting the mission timing, the committee also considered mission costs relative to anticipated 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 (see Box 2.2). However, the committee decided not to include possible cost sharing by international partners as such relationships are sometimes difficult to quantify. Especially given the difficult fiscal environment, the committee believes NASA and NOAA will need to redouble their efforts to develop international partnerships. We also note that NASA's piecemeal approach to such partnerships in the past has reduced the efficiency of the program.

BOX 2.2 ESTIMATING COSTS FOR MISSIONS

One of the difficult challenges for the panels was creating an integrated mission set that is *affordable*, especially given the relatively large number of needed observations. The cost of any given Earth science mission depends on the particular requirements associated with its payload (mass, power, data rate, etc.) and architecture choices (orbit, launch vehicle, downlink scenarios, etc.). Instrument complexity (e.g., detector types, cooling or heating requirements, component redundancy requirements, moving components) can also significantly drive cost. Sophisticated mission cost estimation tools have been developed by NASA and a number of aerospace companies; the performance of these tools is greatly dependent on how well the detailed science and instrument requirements and technology readiness levels are known at the time of estimation.

Responses to the RFI submitted to the panels were valuable for developing individual mission costs; however, a uniform approach to cost estimation (based mainly on known costs for many current and past Earth science missions) was used by the panels to ensure a level of consistency across the set of missions. In consultation with NASA mission designers, a budget spreadsheet was developed to identify all of the primary mission cost components, including instruments, spacecraft, launch vehicle, system engineering and management, integration and test, ground data system, mission operations, data downlink and archiving, science team, and data validation. The major cost dependencies of each component were identified and the likely total cost ranges for mission components were established based on data from current and past missions. For example, the spreadsheet included a choice of launch vehicle (i.e. Pegasus, Minotaur IV, Taurus, Delta II, Delta IV, Atlas V) that depended on the selected orbit and payload mass requirements. By training the costing tool with actual mission cost information, the panels believe that given the assumed measurement requirements, cost estimates for the recommended missions vary from ± 50% for the smallest missions to ± 30% for the larger mission category. Of course, the cost estimates will depend directly on the exact measurement requirements for the eventual missions. The cost uncertainty rises for missions scheduled later in the next decade and for missions with the greatest technology development needs.

Nevertheless, the estimates provided in this study set targets for each mission that lead to an overall affordable program. The panels recognize that the missions afforded under the estimated costs will be ones that respond to the main scientific requirements articulated in the panel chapters, 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 entire mission trade space.

Clearly, more detailed cost estimates are needed that examine the full range of mission trade-offs. Where possible within budget constraints, the augmentation of the specified set of science observations with additional desired observables should be considered; however, NASA and the scientific community must avoid "requirement creep" and the subsequent damaging cost growth.

Given the relatively large uncertainties attached to cost and technology readiness estimates, the committee chose to sequence missions among three broad decadal time periods, namely, 2010 to 2013, 2013 to 2016, and 2016 to 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 humidity sounding, 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. To avoid the problems associated with inadequate technology readiness, out-year missions should begin sooner rather than later and exploit the early timeframe to strengthen the technological foundation for the mid- and long-term missions. The committee recognizes that providing a longer mission timescale to enable development of technologies for those missions is only one part of the challenge. In addition, there must be specific funding for a focused technology program specifically designed to mature the requisite technologies in the preceeding time periods. Such funding must be in addition to NASA's existing basic technology development program within its Earth Science Technology Office (ESTO), and should be of comparable magnitude to the general program. The committee included this focused technology program when it considered the out-year budget needs (see Figure 2.7b). The committee also believes that establishing a clear mission set and schedule will allow for a more effective and focused technology program than was possible with the NASA program over the past 5 years.

Large uncertainties are also associated with attempts to factor in international partner missions in the timing of U.S. missions during the next decade. At the beginning of the next decade, the committee recognized international plans for GCOM-C (2011) and EarthCARE (2012) missions aimed at observing aerosol and clouds. As a result, the committee factored these plans into its decision to target a later time period 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 internationally-developed instruments on various launch opportunities.

The committee's recommended observational strategy, consisting of 14 missions for implementation by NASA, two missions for implementation by NOAA and 1 mission (i.e. CLARREO) with separate components for implementation by NASA and NOAA, is summarized in Tables 2.1 (NOAA portion) and 2.2 (NASA portion). The suggested observing strategy is consistent with current national strategy as expressed in the USGCRP/CCSP and GEOSS. Most importantly, the observing strategy enables major progress across the range of important societal issues, as illustrated in Figure 2.2. The number of recommended missions and associated observations is only a fraction of the number of currently operating Earth missions and observations (see Figure 2.6). *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.*

The overall cost to implement the recommended NASA program (~ $7B over twelve years for the 15 missions) is estimated to exceed currently projected program resources, but fits well within funding levels provided to NASA Earth Science as recently as 2000 (Figures 2.5 and 2.7a). The committee believes that a return of NASA Earth Science funding levels to those experienced at the end of the 20th century is essential for addressing the emerging societal challenges in the 21st century. In order to meet the ambitious schedule laid out in the committee's plan, especially in the 2010 to 2013 timeframe, initial investments in technology and mission development must begin as soon as 2008. Accordingly, the committee sees the need for a rapid growth in the NASA Earth Science budget from approximately $1.5B/yr to $ 2B/yr beginning in 2008 and ending no later than 2010, as shown in Figures 2.7a and 2.7b.

Severe budget problems within the NOAA NPOESS program, which carry budget liens against the program well into the next decade, make it difficult for the committee to gauge the capacity of NOAA to implement additional Earth science missions. In view of this uncertainty, the committee recommends an extremely modest set of new operational missions for implementation by NOAA, with relatively small cost implications (Figure 2.8). Nevertheless, implementation of the set of recommended missions, in concert with the current reduced plan for NPOESS, will ensure substantial continuity, through at least 2020, for all of the desired Environmental Data Records originally targeted by the NPOESS program (see Table 2.5). Broader issues associated with long-term data records for research and applications are discussed more fully in Chapter 3. In addition, as noted earlier, a strategy to recover lost NPOESS capabilities, especially those important for climate-related research, will be the subject of a follow-on NRC study.

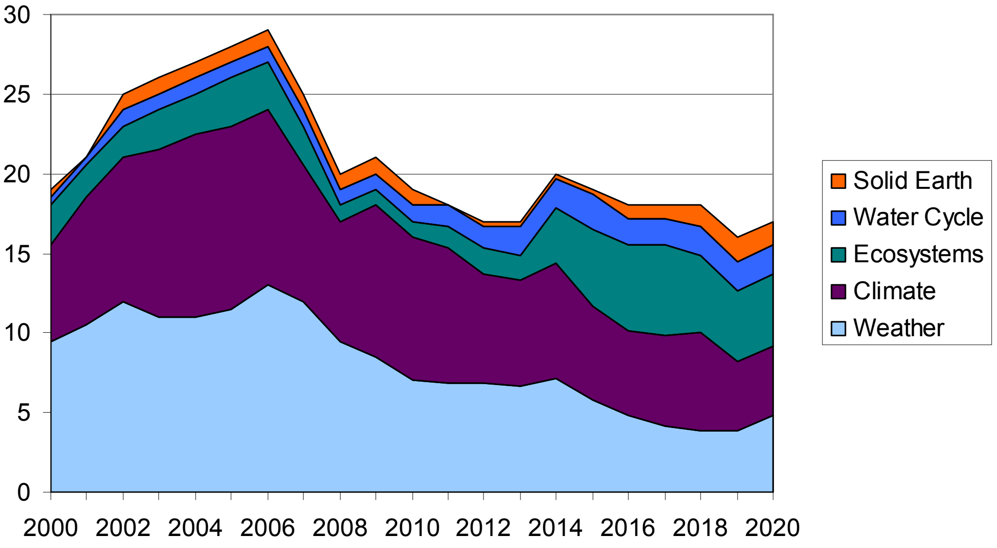


FIGURE 2.6a Space-based missions in the current and next decade. The set of recommended missions provide more uniform focus across the science challenge areas. All of the recommended missions are assumed to operate for seven years (three year nominal mission plus four years of extended mission). The partitioning of the missions into science themes was based on the committee's subjective judgment. Many individual missions were judged to serve multiple themes and were partitioned accordingly. 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.

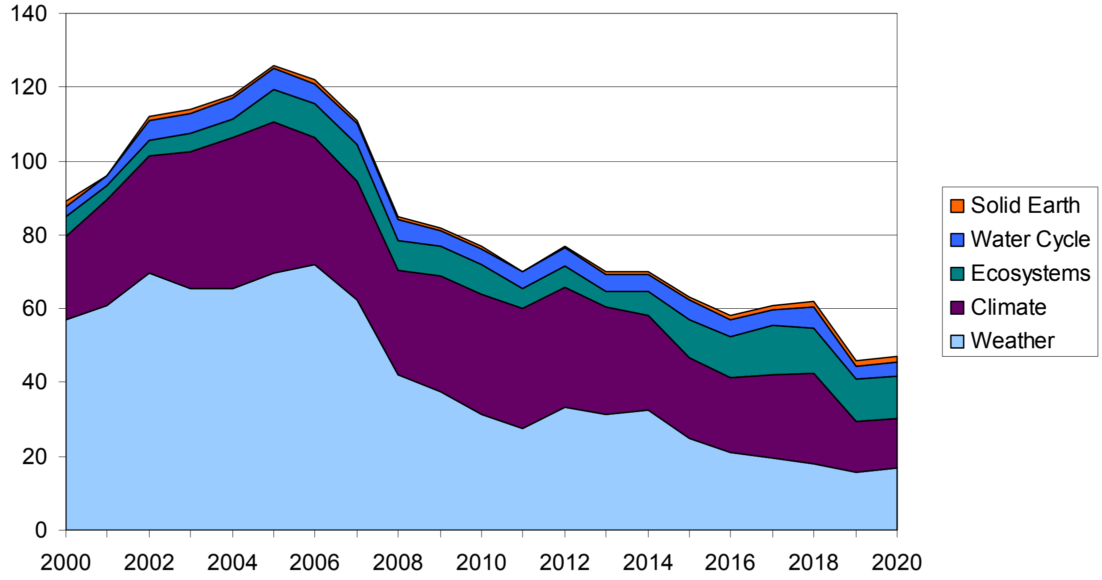


FIGURE 2.6b Space-based instruments in the current and next decade. The set of recommended missions provide more uniform focus across the science challenge areas. All of the recommended missions are assumed to operate for seven years (three year nominal mission plus four years of extended mission). The partitioning of the missions into science themes was based on the committee's subjective judgment. Many individual missions were judged to serve multiple themes and were partitioned accordingly. 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.

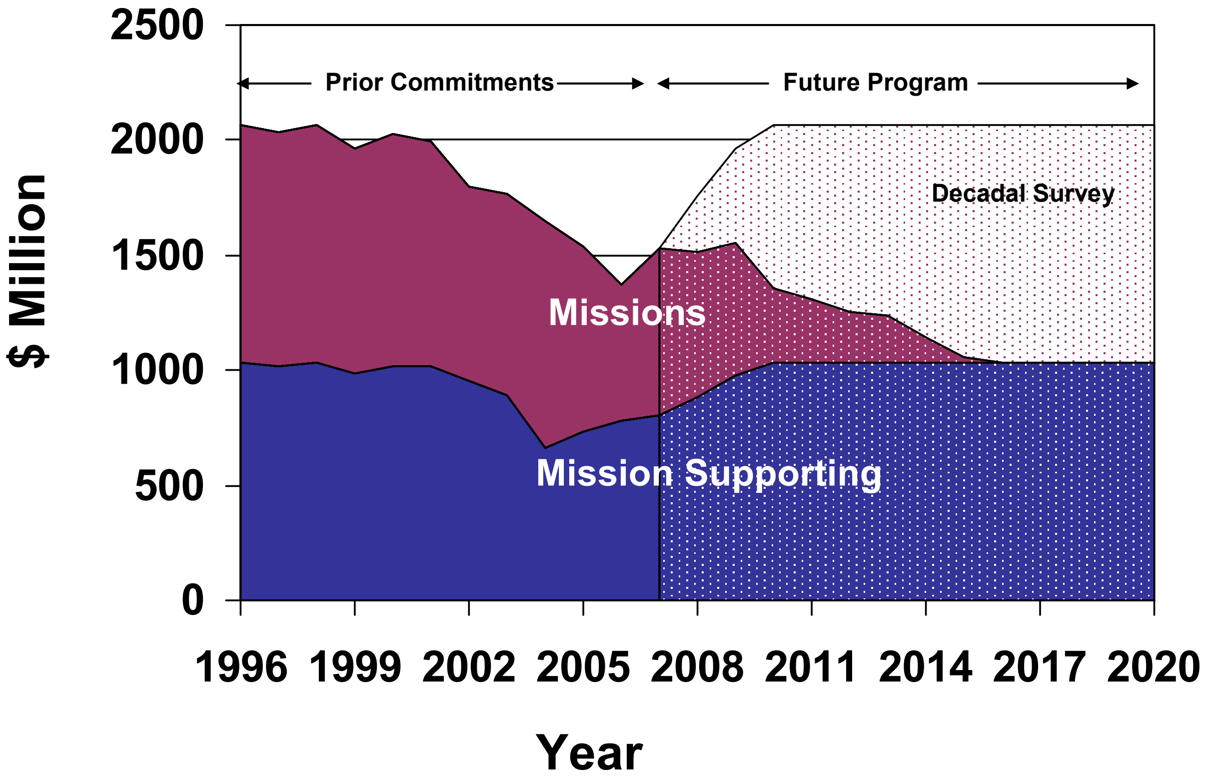


FIGURE 2.7a The NASA budget for Earth Science for the period 1996 to 2020 showing both the decline in funding during the current decade and the increase required to implement the committee's recommendations (in fixed FY2006 dollars). The white dotted areas represent future commitments to ongoing missions and research and analysis efforts. The red dotted "Decadal Survey" area represents the budget wedge that would support the Committee's recommendations regarding missions and technology development in the next decade.

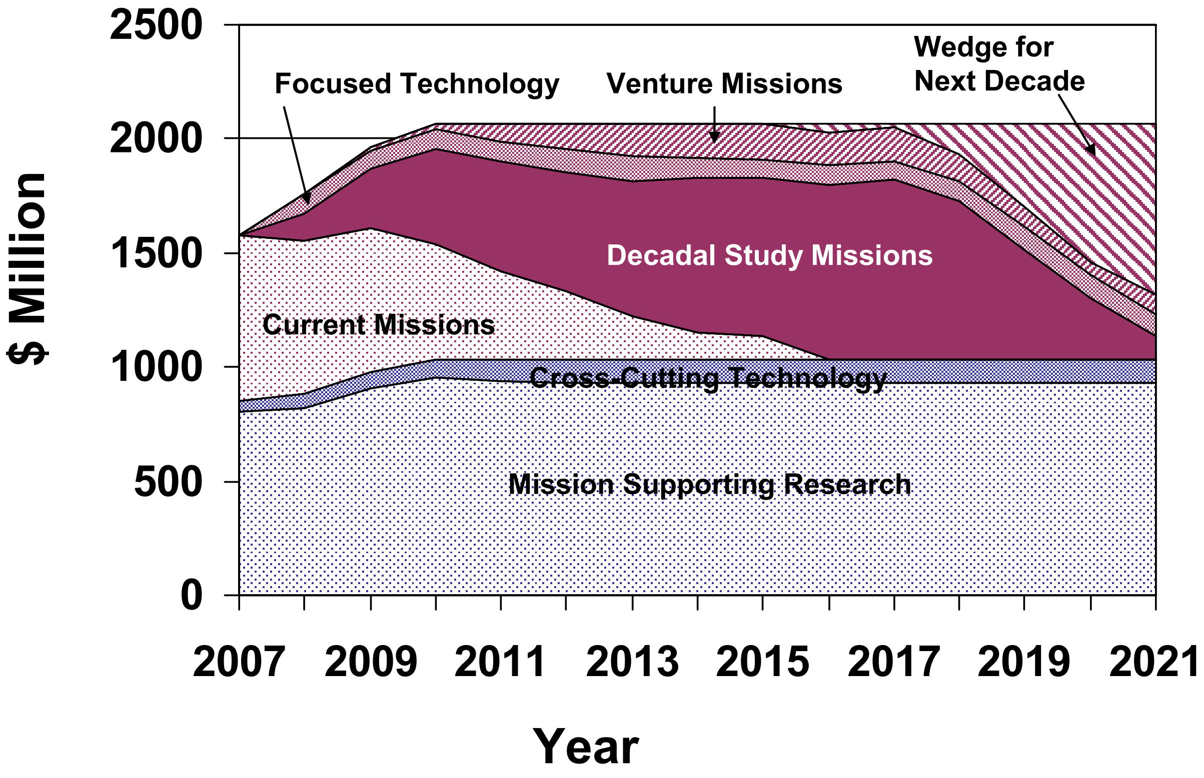


FIGURE 2.7b Detailed view of the NASA budget for Earth Science for the period 2007 to 2020 required to implement the committee's recommendations (in fixed FY2006 dollars). Approximately $7B is phased between 2008 and 2021 to support the 15 missions recommended to NASA. A mission-focused technology line of approximately $100M/year is included to reduce risk associated with the recommended missions. Note: The new class of recommended missions, "Venture," assumes $200 million for a new start every two years, and each mission assumed to phase in over a 5-year period. The new starts could, for instance, include two $100M level type efforts or one larger $200M activity.

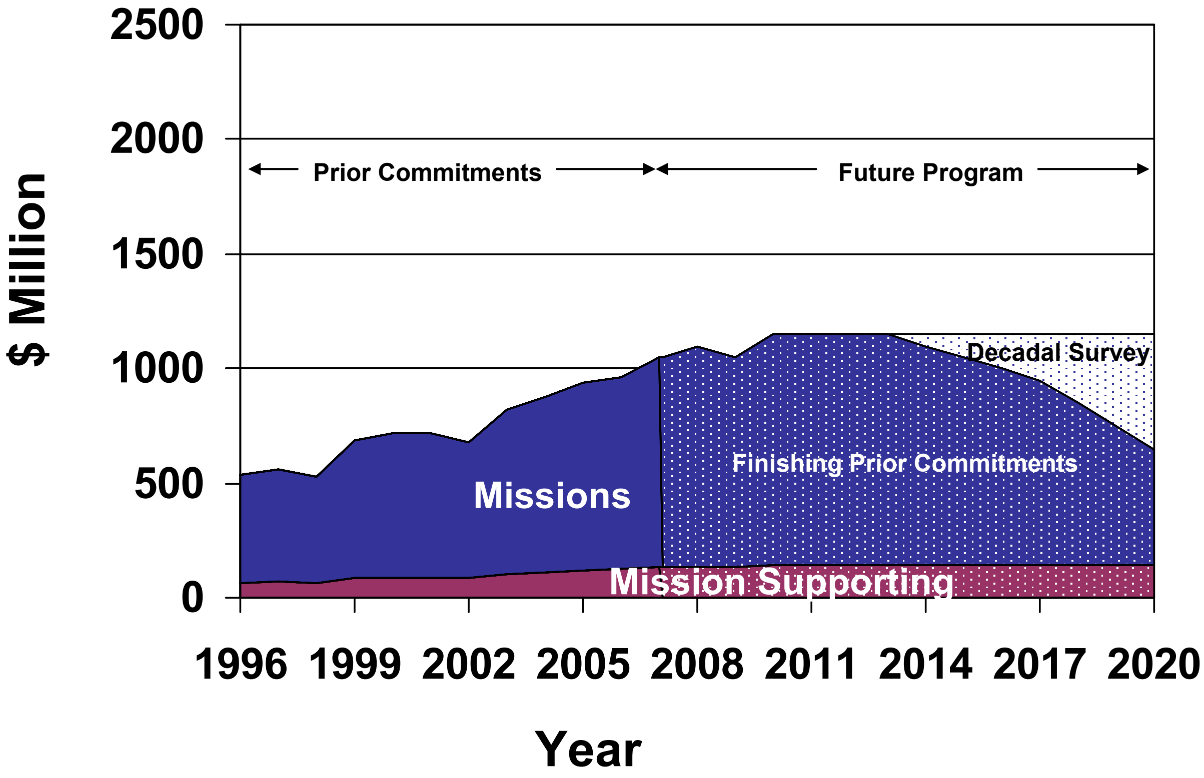


FIGURE 2.8a The NOAA NESDIS budget for the period 1996 to 2020 showing the increase during the current decade to support NPOESS and GOES as well as the maintenance of the current levels required to implement the committee's recommendations (in fixed FY2006 dollars). The white dotted areas represent commitments to ongoing NPOESS and GOES projects. The blue dotted area "Decadal Survey" area represents the budget wedge that would support the Committee's recommendations regarding missions and technology development in the next decade.

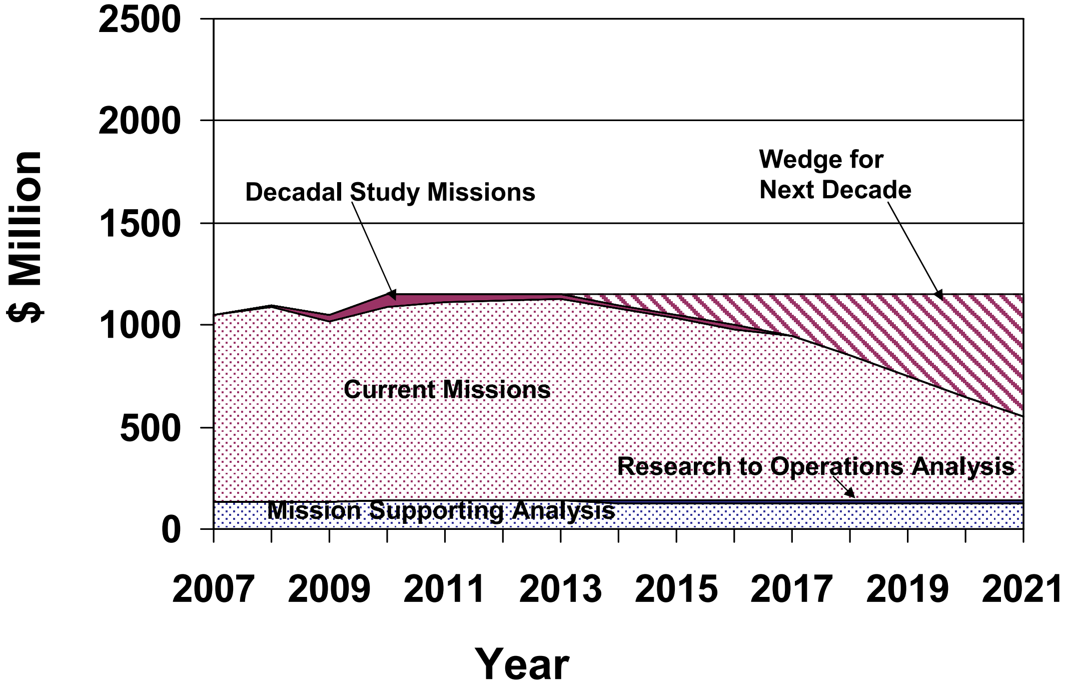


FIGURE 2.8b A detailed view of the NOAA NESDIS budget for the period 2007 to 2020 required to implement the committee's recommendations (in fixed FY2006 dollars). Small wedges are introduced to implement the recommended missions in Table 2.1 and to perform analysis on approaches to implementing new cost-effective operational measurements based on research instrument development.

TABLE 2.5 Contributions of recommended missions to continuation or expansion of Environmental Data Records (EDRs) as defined by the NPOESS Integrated Operational Requirements Document (2001). Current status of NPOESS's planned capabilities to obtain the EDRs is also shown. NOTE: MetOp contributions to EDRs and space weather-related EDRs are not listed here.

Descoped/Degraded EDR	**NPOESS Status**	**Relevant ESAS Contribution**
Soil moisture	Degraded	SMAP
Aerosol refractive index/single-scattering albedo and shape	Demanifested	ACE
Ozone total column/profile	Reduced Capability (Column only)	GACM
Cloud particle size distribution	Demanifested	ACE
Downward LW radiation (surface)	Demanifested	CLARREO
Downward SW radiation (surface)	Demanifested	CLARREO
Net solar radiation at TOA	Demanifested	CLARREO
Outgoing LW radiation (ToA)	Demanifested	CLARREO
Solar irradiance	Demanifested	CLARREO
Ocean wave characteristics/Significant wave height	Reduced Capability	XOVWM
Sea surface height/topography - basin scale/global scale/mesoscale	Demanifested	SWOT

EDR dependent on CMIS replacement	**NPOESS Sensor**	**Relevant ESAS Contribution**
Atmospheric vertical moisture profile	CrIS/ATMS/CMIS(replacement)	PATH, GPSRO, CLARREO
Atmospheric vertical temperature profile	CrIS/ATMS/CMIS(replacement)	PATH, GPSRO, CLARREO
Global sea surface winds	CMIS(replacement)	XOVWM
Imagery	VIIRS/CMIS(replacement)	HyspIRI
Sea surface temperature	VIIRS/CMIS(replacement)	PATH
Precipitable water/Integrated water vapor	CMIS(replacement)	ACE
Precipitation type/rate	CMIS(replacement)	PATH
Pressure (surface/profile)	CrIS/ATMS/CMIS(replacement)	GPSRO, CLARREO
Total water content	CMIS(replacement)	ACE
Cloud ice water path	CMIS(replacement)	ACE
Cloud liquid water	CMIS(replacement)	ACE
Snow cover/depth	VIIRS/CMIS(replacement)	SCLP
Global sea surface wind stress	CMIS(replacement)	XOVWM
Ice surface temperature	VIIRS/CMIS(replacement)	
Sea ice characterization	VIIRS/CMIS(replacement)	SCLP, ICESat-II

The recommended mission list reflects an integrated and carefully sequenced mission plan that addresses the range of urgent societal benefit areas (Figures 2.9 to 2.17). 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.

As noted above, the committee generally placed technologically-ready and less expensive missions earlier in the sequence of implementation. This strategy both reduces the risk of mission failure and makes optimal use of the emerging budget wedge. In considering each highlighted societal need, it was apparent to the committee that elimination of any of the recommended missions would severely limit gains in at least one, and typically several, important societal need areas. A change to an individual mission, whether forced by budget or technology, or changing user priorities, should cause the implementing agencies to consider the ramifications for the subsequent program to ensure that unacceptable gaps in measurements or other problems are not created.

Detailed recommendations for implementing the observing program are given in the next chapter. Here, we call attention to the fact that 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 not only the need to learn "lessons" from implementing the 17 recommended missions, but also the need to efficiently transition select research observations to operational status and to create space-based observing opportunities aimed at fostering new science leaders and revolutionary ideas. Towards these objectives the committee makes the following recommendation:

Recommendation: U.S. agencies should aggressively pursue technology development that supports 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 (~ $100M - $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 than 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.

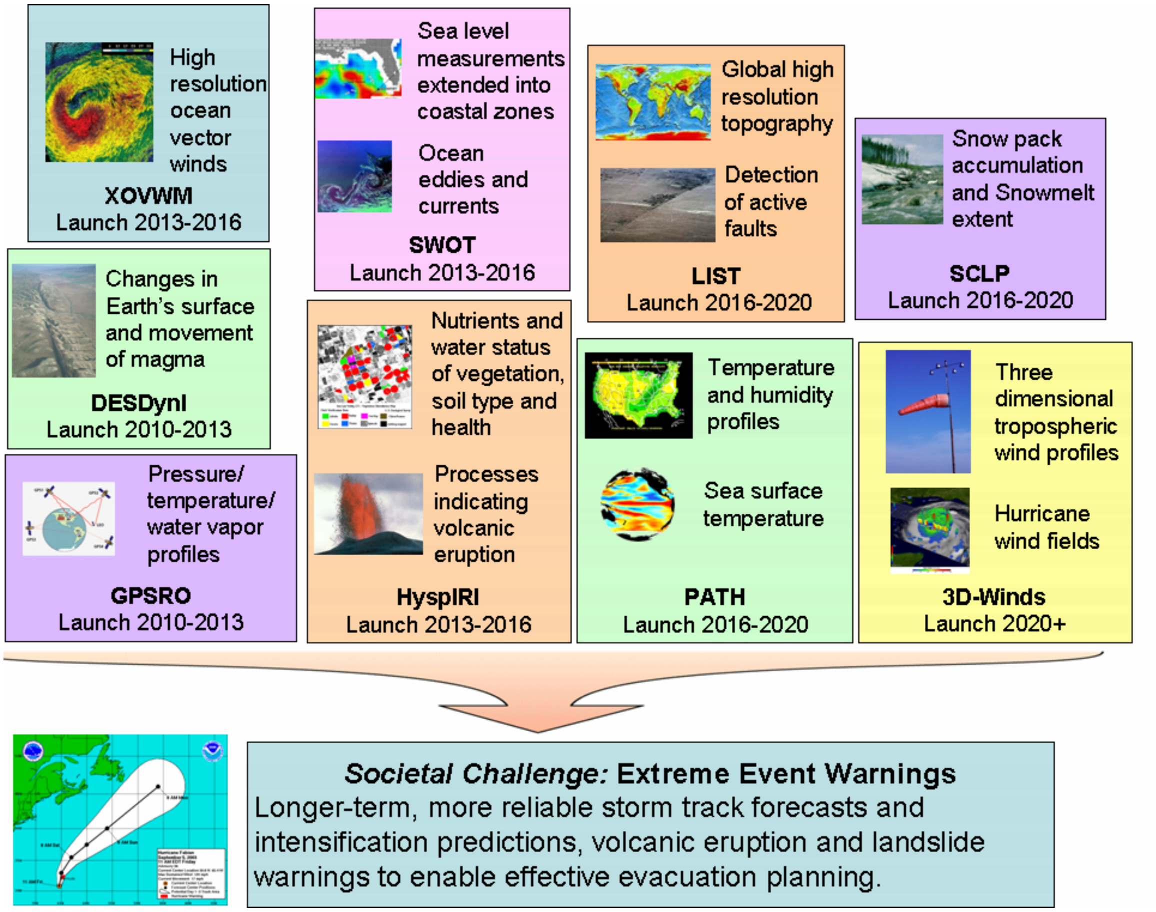
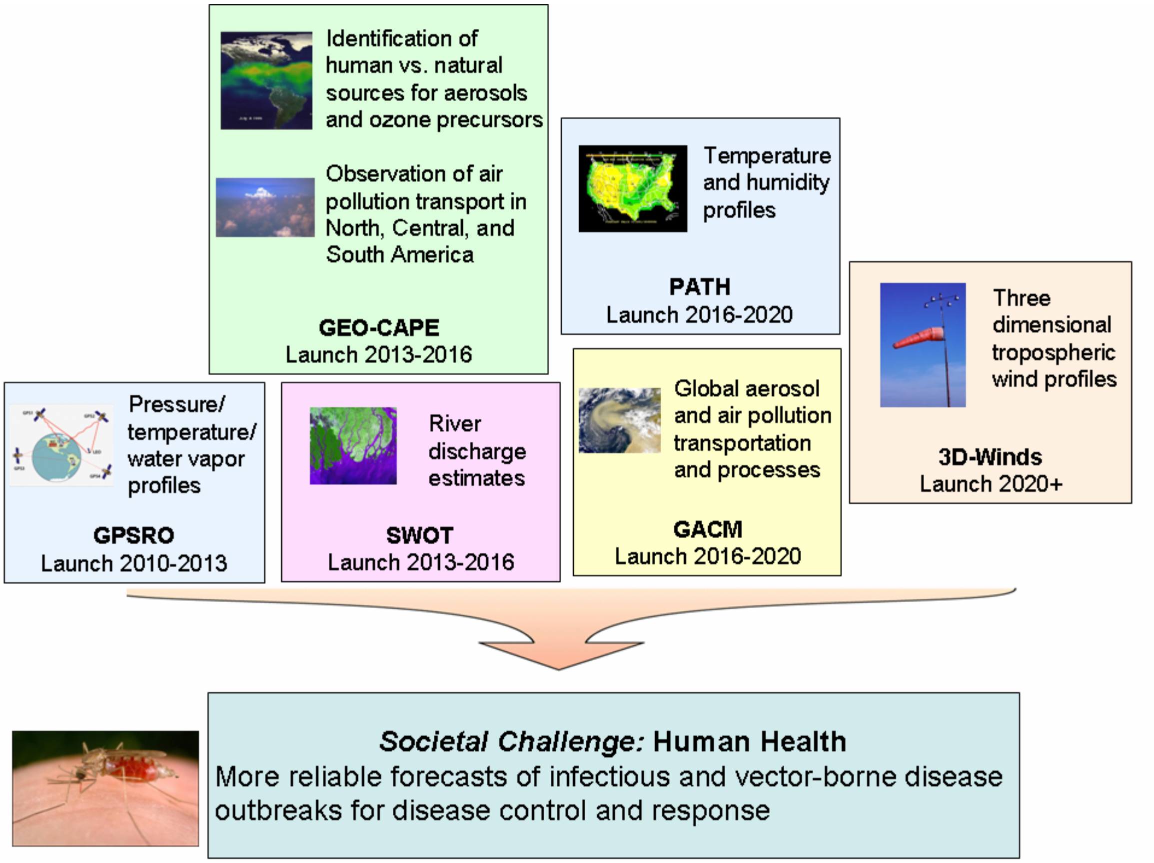


FIGURE 2.9 Recommended missions supporting extreme event warning need.



Identification of human vs. natural sources for aerosols and ozone precursors

Observation of air pollution transport in North, Central, and South America

GEO-CAPE
Launch 2013-2016

Temperature and humidity profiles

PATH
Launch 2016-2020

Three dimensional tropospheric wind profiles

3D-Winds
Launch 2020+

Pressure/ temperature/ water vapor profiles

GPSRO
Launch 2010-2013

River discharge estimates

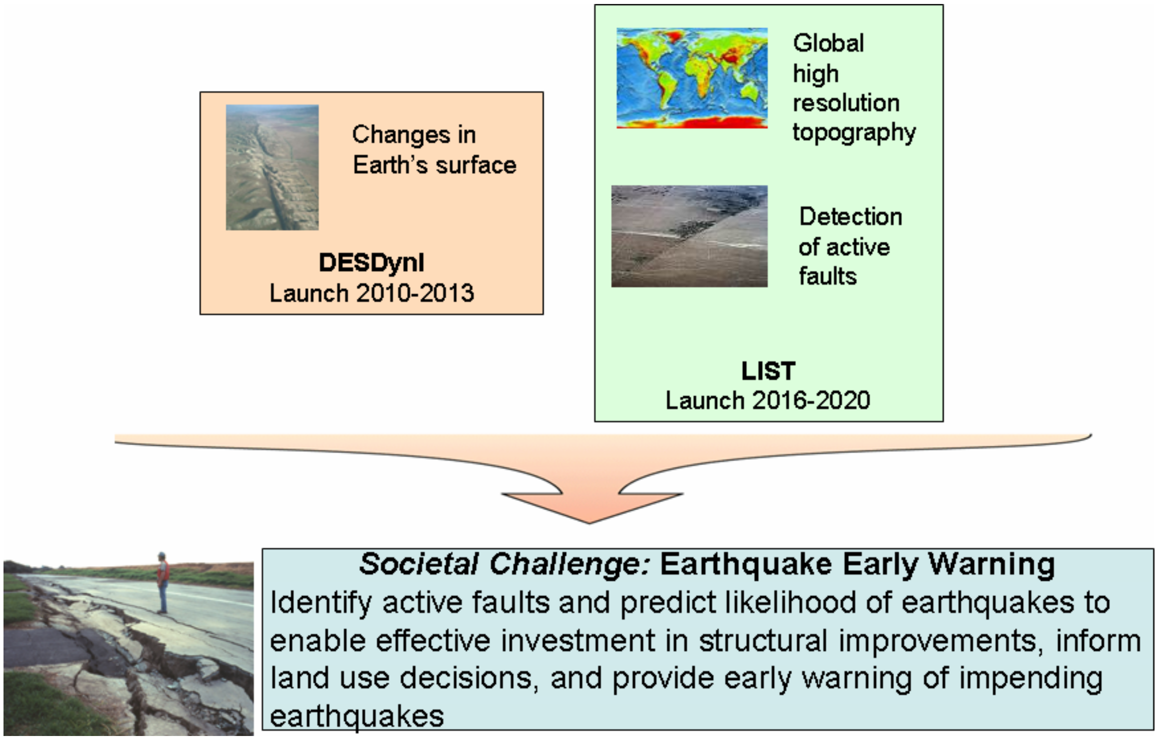
SWOT
Launch 2013-2016

Global aerosol and air pollution transportation and processes

GACM
Launch 2016-2020

***Societal Challenge:* Human Health**
More reliable forecasts of infectious and vector-borne disease outbreaks for disease control and response

FIGURE 2.10 Recommended missions supporting human health needs.



Identify active faults and predict likelihood of earthquakes to enable effective investment in structural improvements, inform land use decisions, and provide early warning of impending earthquakes

FIGURE 2.11 Recommended missions supporting earthquake early warning need.

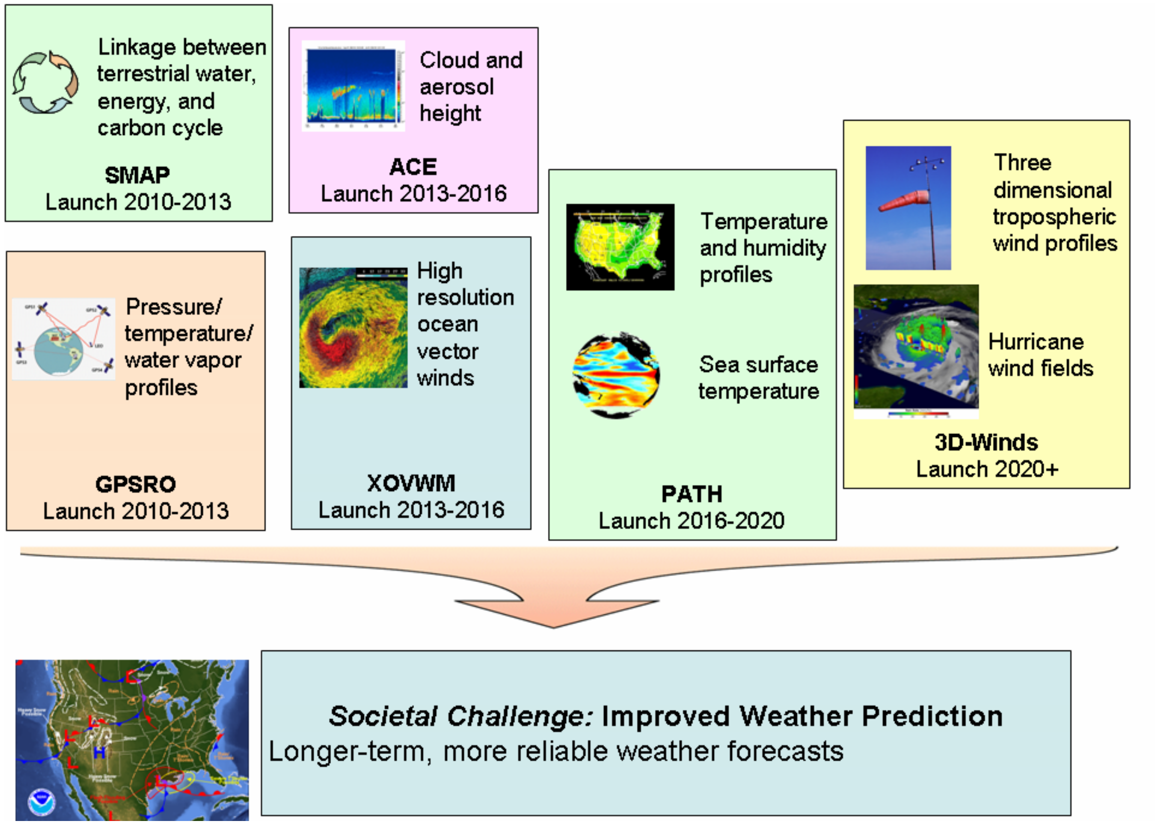


FIGURE 2.12 Recommended missions supporting improved weather prediction need.

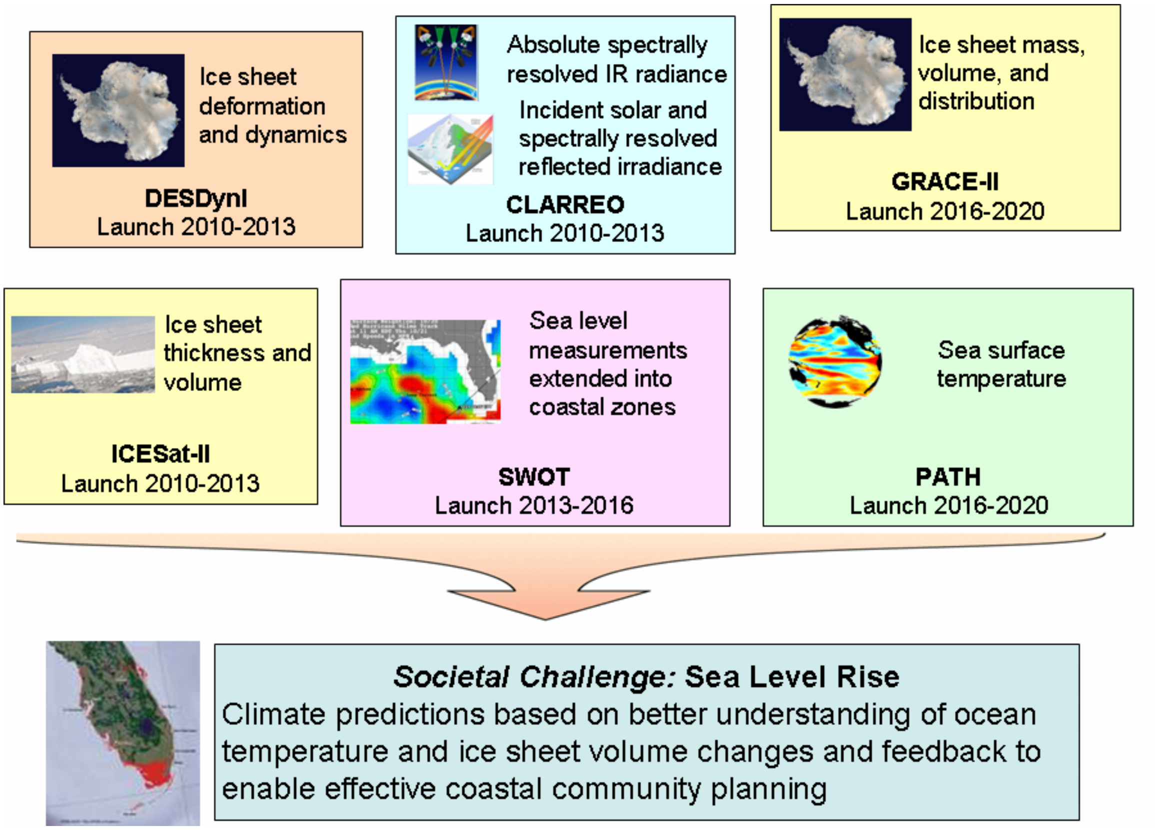


FIGURE 2.13 Recommended missions supporting sea level rise prediction need.

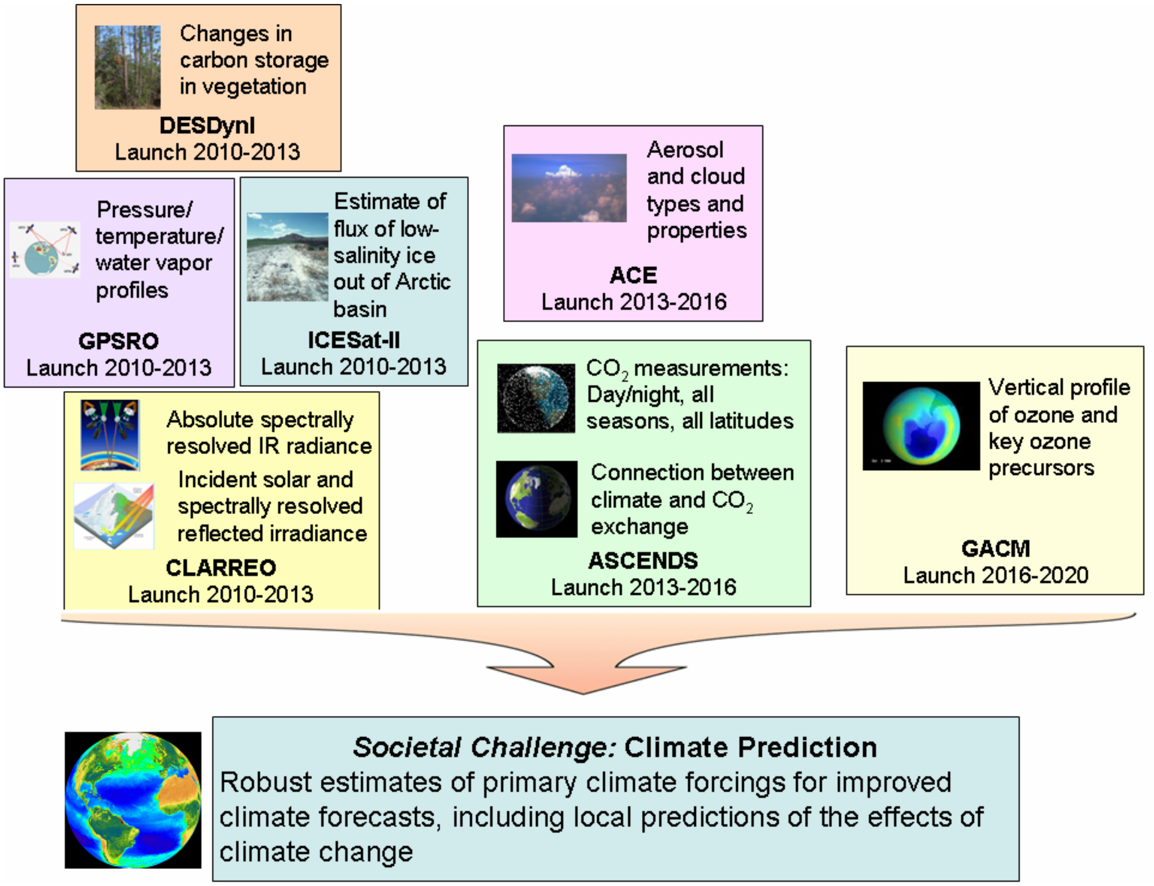


FIGURE 2.14 Recommended missions supporting climate prediction need.

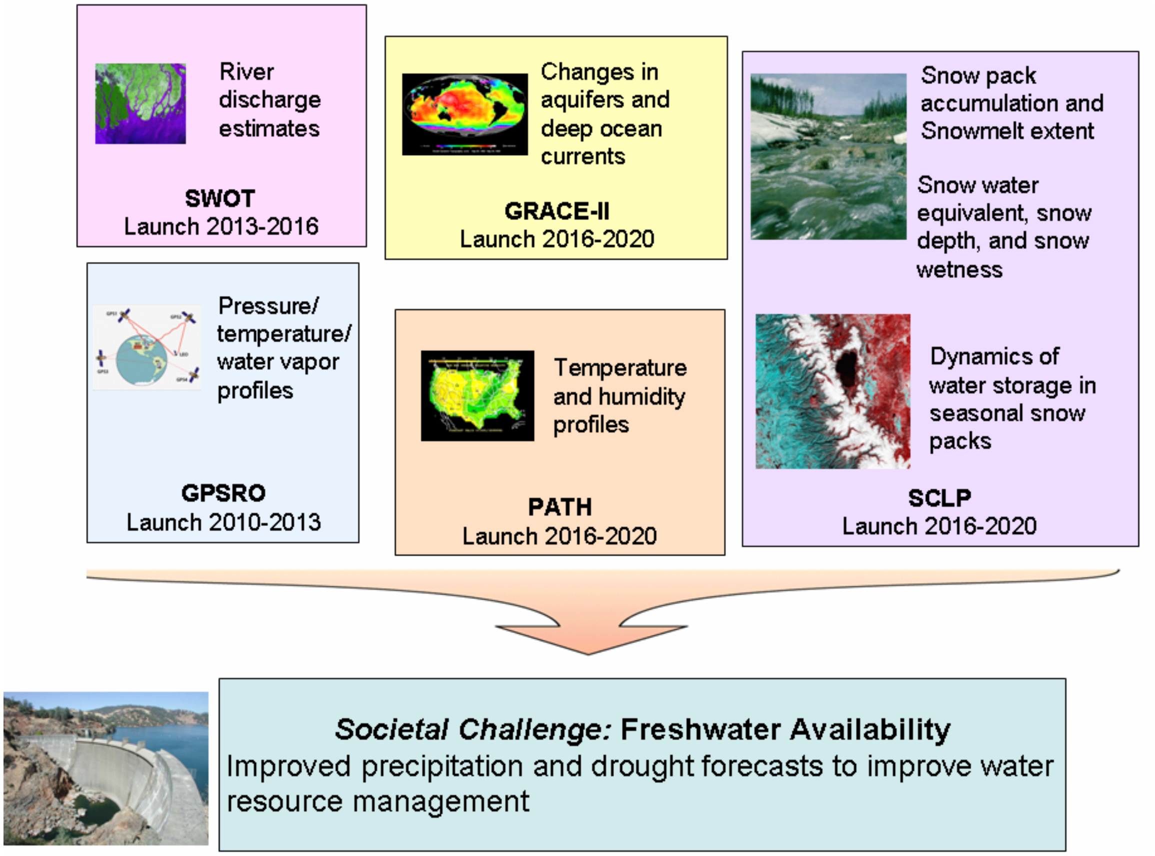


FIGURE 2.15 Recommended missions supporting fresh water availability need.

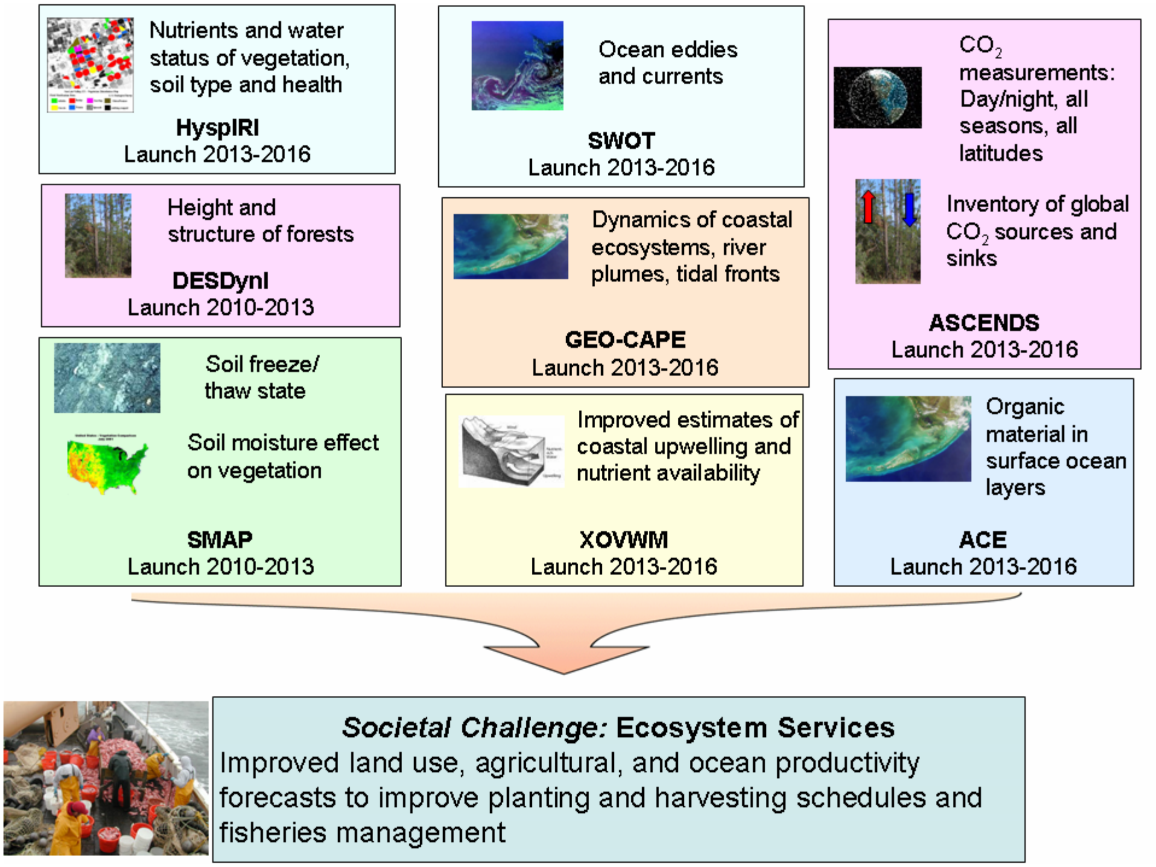


FIGURE 2.16 Recommended missions supporting ecosystem services need.

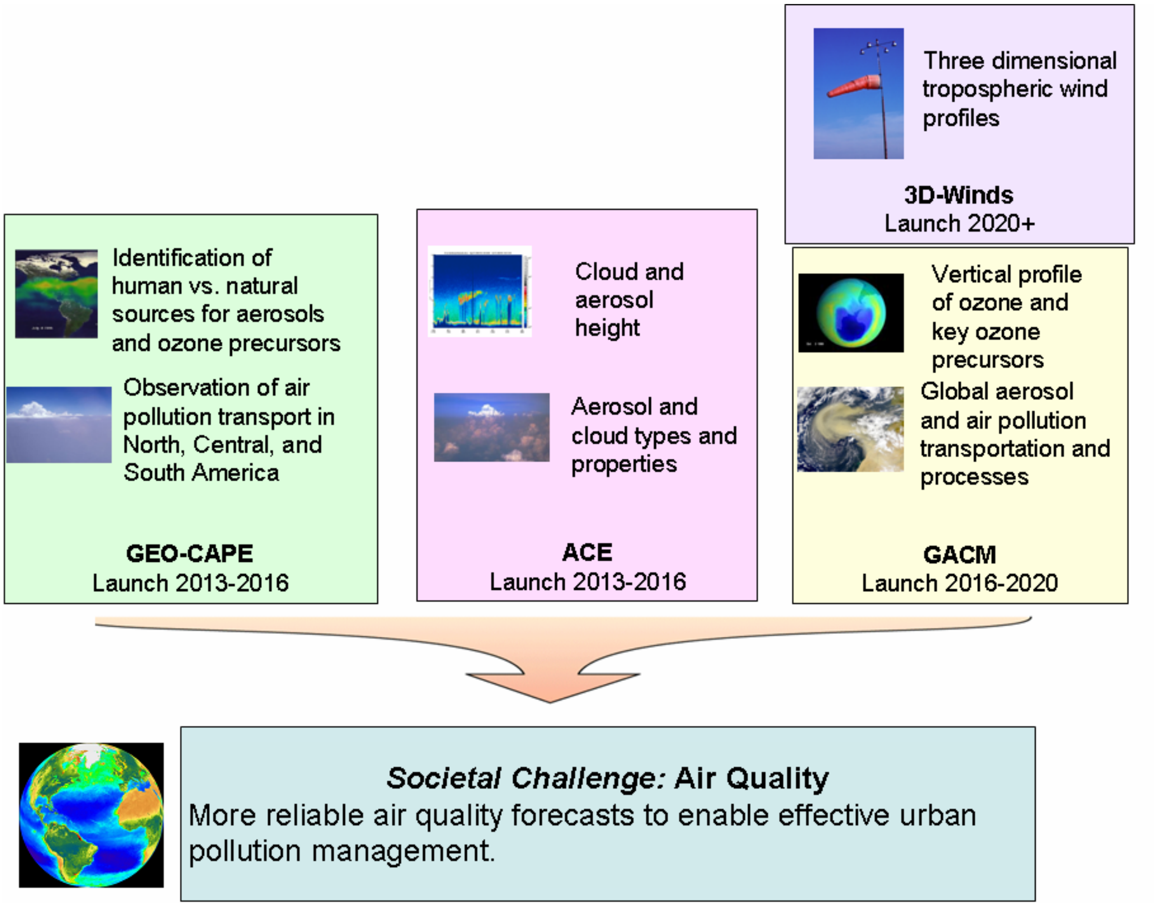


FIGURE 2.17 Recommended missions supporting air quality need.

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3

From Satellite Observations to Earth Information

The mission plan presented in Chapter 2 aims 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. *However, the missions are but one part of a larger program that is required to translate raw observations of Earth into useful information.* In this chapter, the committee highlights key additional elements of the overall program that must be supported to achieve the decadal vision. These include: (1) sustained observations from space for research and monitoring, (2) surface-based (land and oceans) 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, education and training, and other activities that strengthen and sustain the knowledge and information system. These elements are each complex and deserve significant attention by the federal agencies, academia, and the private sector, but a detailed analysis and set of recommendations associated with each of them are well beyond the scope of this report. Therefore, we summarize them here to note their essential importance as parts of a complete program in Earth science and applications.

SUSTAINED OBSERVATIONS FOR OPERATIONS, RESEARCH, AND MONITORING

Scientific breakthroughs are often the result of new exploratory observations, and therefore new technology missions stimulate and advance fundamental knowledge about the planet. Analysis of new observations can both test hypotheses developed to elucidate fundamental mechanisms and lead to the development of models that explain or predict important Earth processes. The data from these new technology missions sometimes hint at changes in Earth that are critical to our well-being, such as declining ice cover in the Arctic Ocean, developing holes in the protective ozone layer, or rising sea level. To determine the long-term implications of the changes or to uncover slowly evolving dynamics, the measurements must be continued, usually with one or more follow-on missions. For example, the long-term, global record of vegetation's photosynthetic activity spans multiple sensors. This record is proving to be critical for identifying changes in length of growing seasons and productivity in response to climate change. Such *sustained* observations allow scientists to document change, to determine the processes responsible for the changes, and to develop predictions. They also are often needed to allow resource managers to assess the ongoing impact of these changes on society.

Sometimes data from a new technology mission become critical to an operational system, such as the wind speed and direction measurements from NASA's QuikSCAT mission and precipitation measurements from NASA's TRMM, both of which are used in weather forecasting. An obvious but often difficult consequence is that these measurements need to be transitioned into *operational* systems and maintained for many years. This is a recognized and well-studied challenge, but the record of transitioning new technology into the operational system is, at best, mixed.[1]

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[1] Transition failures have been exhaustively described in previous reports (NRC, 2000 and NRC, 2003b), and we support those analyses and recommendations.

There is also 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. Likewise 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.

Unfortunately, our ability to reach across the overlapping categories of exploratory, sustained, and operational Earth observations has not proven very successful and the recent experience with NPOESS is particularly problematic and revealing in the area of sustained measurements (Box 3.2).

BOX 3.1 SUSTAINED RESEARCH OBSERVATIONS AND THE CHALLENGE OF CLIMATE RECORDS

Sustained measurements are needed to distinguish short-term variability in the Earth system from long-term trends. Sea level, for example, is monitored using a radar altimeter that measures the height of the ocean relative to a fixed reference level. Sea level must be measured with accuracy sufficient to distinguish the 50 mm seasonal variations from the 3 mm climate signal (Figure 3.1a). The exceptionally long data record of the TOPEX/Poseidon (T/P) mission gave an estimate for the global sea level rise of about 3 mm/year. Had T/P failed late in 1997, the increase in sea level in 1997 would have appeared to be an acceleration of sea level rise, rather than an anomalous peak in a longer-term trend. A follow-on mission to T/P, Jason-1, a cooperative effort of the U.S. and French space and operational agencies, was launched before T/P failed. An overlap period of four years between the two missions allowed the science and engineering teams to detect and correct for a slow degradation of the T/P tracking system to give a continuous record of sea level rise.

This overlap is particularly important in making climate observations. Design of climate observing and monitoring systems from space must ensure the establishment of global, long-term climate records, which are of *high accuracy, tested for systematic errors on-orbit, and tied to irrefutable standards* such as those maintained in the U.S. by the National Institute of Standards and Technology. For societal objectives that require long-term climate records, the accuracy of core benchmark observations must be verified against absolute standards *on-orbit* by fundamentally independent methods, such that the accuracy of the record archived today can be verified by future generations. Societal objectives also require a long-term record not susceptible to compromise by interruptions in that data record. Finally, we must recognize that climate observations are different from weather observations. For example, the continuing debate over the reliability of surface temperature records and the community's inability to establish the upper air temperature record over the past several decades stem from attempting to create climate records from what are essentially weather-focused observations.

This issue of sea level rise also illustrates the importance of sustained *in situ* measurements. Observations of ocean temperatures from a network of drifting buoys, Argo, provided the foundation for estimating the contribution to sea level rise from a warming ocean (about 1.7 mm/year). The residual of 1.3 mm/year (Figure 3.1b) is the result of other processes, presumably melting ice sheets, a contribution that may accelerate the rate of sea level rise in the future. This residual sea level rise can then be compared with estimates of changes in ice volume to verify this presumption. Trends in all of the measurements are needed to calibrate climate models that predict future changes in sea level and in other climate variables. This example illustrates the importance of avoiding gaps in the data record, of coordinating satellites with other measurement programs, and of supporting science and engineering teams to maintain and interpret the observations.

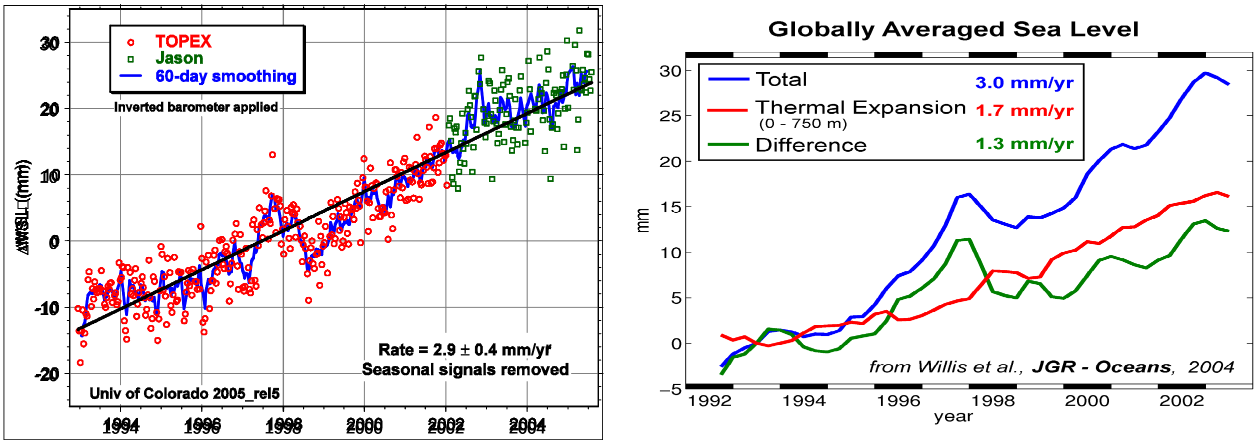

FIGURE 3.1 (a) Estimates of global sea level from the TOPEX/Poseidon (red) and Jason (blue) missions. The total rate of rise is about 3 mm/year. (b) An estimate of the contribution to sea level from expansion by the warming ocean (1.7 mm/year) from Argo drifting buoys. The difference of 1.3 mm/year is from the melting of the polar ice sheets. SOURCE: Courtesy of NASA.

BOX 3.2 NPOESS, EOS, AND THE SEARCH FOR SUSTAINED ENVIRONMENTAL MEASUREMENTS

The NPOESS program was, at the outset, driven by a single imperative—*convergence* of weather measurements, which would eliminate duplication in observations in the early afternoon and still maintain the same temporal robustness that characterized the combination of POES and DMSP. The cost savings from eliminating duplication could then be reallocated to improve weather observations and models.

By the mid-1990s, it was clear that NASA would not sustain a *long-term*, broad, EOS-like observational and information processing program; therefore, the community developed a new strategy for obtaining climate measurements from NPOESS. This lead to a second NPOESS program imperative—*operationalizing* a climate observing system, which would enable sustained, long-term measurements for climate studies and other environmental issues. However, this was done *after* consideration of optical designs, orbits, and data systems needed for weather forecasts; additional requirements for climate were then added, invoking very different objectives and thus requirements for optical designs, orbits, and other mission and instrument characteristics.

Attempting to satisfy these two imperatives simultaneously constituted a difficult challenge, both technically and programmatically. Part of the challenge arose from trying to balance the inherent mismatch of data requirements. Weather forecasts demand frequent observations and rapid data dissemination, while climate operations and research demand accurate and consistent long-term records. The added requirements for instrument stability and accuracy, driven by the more stringent climate requirements, placed additional challenges on the instruments. Moreover, the expanded mission's requirements to address climate and other environmental issues established demands for additional observations such as ocean altimetry, which were not weather-related *per se*. This expanded the scope of the mission, increased its complexity, and added to the pressure for larger platforms. Finally, although the mission of one of the operational partners (Department of Commerce/NOAA) included climate and other broad environmental issues, the mission of the other operational partner (Department of Defense/Air Force) did not. In turn, this led to conflicting priorities between the two agencies, which by law were required to share program costs on a 50-50 basis.

Climate Data Records (CDRs) are time series of measurements of sufficient length and accuracy to determine climate variability and change.[2] Such records are invaluable, as frequently an examination of the causes of changes in Earth processes requires long, stable, accurate records of several variables. For example, in order to investigate links between hurricane intensity and global warming (Emanuel, 2005; Webster et al., 2005) by determining whether there is a connection between the power of hurricanes and a warming ocean, it is necessary to have long and accurate records both of hurricane wind speeds and ocean temperatures; Box 3.1 provides additional examples.

In addition to an observation system that routinely makes critical measurements, obtaining CDRs requires a substantial commitment by a team of experts to support data reprocessing, the resolution of differences in sensor characteristics, and evaluation of data in research and applications. For example, sea surface temperatures were improved through several joint agency efforts (e.g., NOAA-NASA Pathfinder program, GODAE/NOPP) and, more recently, by combining infrared measurements with those from a microwave radiometer that can measure through the ubiquitous cloud-cover (GODAE High Resolution SST (GHRSST) Project.[3])

Calibration and validation in the context of CDRs can be considered a process that encompasses the entire system, from sensor to data product (NRC 2004b). The objective is to develop a quantitative understanding and characterization of the measurement system and its biases in time and space, which involves a wide range of strategies that depend on the type of sensor and data product. For example, for ocean color where the dominant satellite-sensed signal is from the atmosphere, monthly viewing of the moon is essential to quantify changes in sensor response.

In its Interim Report, this committee recommended that NOAA embrace its new mandate to understand climate variability and change by asserting national leadership in applying new approaches to generate and manage satellite CDRs, developing new community relationships, and ensuring long-term accuracy of satellite data records.[4] The committee also noted that NOAA had stated its intention to use NPOESS to create CDRs. However, as detailed elsewhere in this report (see, for example, Table 2-5 and discussions in Chapter 9), the NPOESS program has been significantly descoped with a focus only on "core" missions related to weather. Therefore, the committee reiterates its previous recommendation:

Recommendation: 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.

Experience with the Landsat series of satellites provides another prime example of the difficulty in transitioning an instrument technology along the path from exploratory, to sustaining, and eventually to operational missions. Continuing Landsat-type land surface measurements does not fall within the charter of NOAA, requires greater budget capacity than is available within USGS, and is incompatible with NASA's mission of developing new science and technology. As a consequence, the Landsat 7 follow-on will suffer a data gap that will be highly detrimental to users of these critical long-term sustained measurements. Furthermore, over the past four years the program was moved from NASA to NPOESS and back to NASA, where it is now moving slowly forward.

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[2] The understanding of many Earth processes requires sustained and carefully-calibrated data, including a continuous and consistent measurement history, and hence the challenge extends beyond the issue of climate.

[3] Proceedings from the Fourth GODAE High Resolution SST Pilot Project Workshop, Pasadena, California, 22-26th September, 2003. GHRSST-PP Report No. GHRSST/18 GODAE Report No. 10. Available on the world-wide-web at: <http://dup.esrin.esa.it/files/project/131-176-149-30_20068812258.pdf>.

[4] National Research Council, Climate Data Records from Environmental Satellites: Interim Report, National Academies Press, Washington, D.C., 2004. See also Congressional <http://www.house/gov/science/hearings/ets02/jul24/abbott.htm>.

Fundamental scientific and policy issues, such as related to climate change, that demand difficult and expensive observations require a carefully examined and internally consistent approach if we are to realize and sustain the essential measurements. 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 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 committee notes that a similar recommendation, however addressed explicitly to the Science Mission Directorate (SMD) of NASA, is contained in the NRC review of the SMD draft Science Plan (Box 3.3). **The committee endorses the recommendation stating, "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."**[5]

BOX 3.3 AD HOC COMMITTEE ON REVIEW OF NASA SCIENCE MISSION DIRECTORATE SCIENCE PLAN

For Earth science, the committee[6] recommended:

a. NASA/SMD should incorporate into its Science Plan the recommendations of the NRC Earth science decadal survey interim report, and should incorporate the recommendations of the Earth science decadal survey final report when it is completed.

b. NASA/SMD 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.

c. NASA/SMD should present an explicit strategy, based on objective science criteria for Earth science observations, for balancing the complementary objectives of (i) new sensors for technological innovation, (ii) new observations for emerging science needs, and (iii) long-term sustainable science grade environmental observations.

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

[6] The *Ad Hoc* Committee on Review of NASA Science Mission Directorate Science Plan was established and met July 11-13, 2006, in Washington, DC.

COMPLEMENTING OBSERVATIONS FROM SPACE

Space-based observations provide a global view of many Earth system processes; however, satellite observations have a number of limitations, including spatial and temporal resolution and the inability to observe certain parts of the Earth. Hence, they do not provide a picture of the Earth system that is sufficient for understanding key physical, chemical, and biological processes. Observations from surface-based (land and ocean) and aerial *in situ* sensors complement satellite observations through calibration and validation campaigns, and by making critical measurements in places and with accuracy, precision, and resolution that are not obtainable from space. In addition, satellites do not directly observe many of the changes in human societies that are affected by or affect the environment. The requisite Earth information system therefore requires the following additional types of observations to complement the observations from space.

Surface-based and Suborbital Airborne Observations

Before satellites, the global observing system that supported weather prediction and research[7] consisted primarily of surface-based observing systems over land, ship reports over the ocean, balloon-borne systems such as radiosondes, and aircraft reports. These systems remain important today and constitute a fundamental part of the integrated global observing system (http://www.wmo.ch/web/www/OSY/GOS.html ; Uppala et al., 2005; and Appendix C). Unfortunately, the number of upper-air radiosonde observations is declining in many parts of the world, although this decline is compensated in part by increasing satellite observations (Uppala et al., 2005).

The surface-based network of meteorological observing station in the U.S. is adequate for weather prediction. However, the network is inadequate for climate monitoring and research because of siting, accuracy, and precision issues. To remedy this situation, NOAA is developing the U.S. Climate Reference Network (USCRN, www.ncdc.noaa.gov/oa/climate/uscrn/). The primary goal of this network of approximately 100 climate stations is to provide future long-term homogeneous observations of temperature and precipitation that can be coupled to long-term historical observations for the detection and attribution of present and future climate change. Data from the USCRN will be used in operational climate monitoring activities and for placing current climate anomalies into an historical perspective. The USCRN will also provide the United States with a reference network that meets the requirements of the Global Climate Observing System (GCOS).

Routine aircraft observations play an important role in operational weather forecasting (Uppala et al., 2005). Airborne observations have also played an important research role in the formulation of public policy legislation, or in the systematic testing and improvement of forecast models across broad categories in the Earth Sciences, for example:

- Establishment of the Montreal Protocol limiting the international release of chlorofluorocarbons,
- Limitations on the nitrate, sulfate, carbon, and heavy metal emission from industrial sources,
- Tracking and forecasting of hurricane trajectories and other severe storm systems,
- Monitoring of solid-Earth hazards such as volcanic eruptions and landslides,
- Establishing the mechanistic coupling between dynamics, radiation, and chemistry in the Earth's climate system, and
- Assessment of damage from natural disasters and the establishment of tactics for providing relief to survivors.

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[7] For instance, ground-based networks are also important for creating sustained data in many other scientific areas. Examples include aerosols (i.e., AERONET) stratospheric gases (e.g., NDSC), and Earth geodesy (SLR, VLBI, GPS).

Yet, strikingly, at a time when the scientific and societal need has never been greater for a robust national capability in aircraft research and surveillance, NASA's competence and resources in airborne research facilities has eroded to a point where it is now in significant jeopardy. The decline is measured in terms of increasing limitations on aircraft available for deployment, on decreased support for instrument development, on lack of funds to stage missions, and on a loss of technical infrastructure to execute needed objectives.

To compound the impact of a significantly weakened airborne program, virtually every satellite instrument developed for observations of the Earth from space was first conceived and tested on an aircraft platform. In addition, the vitality of the graduate programs in experimental science and engineering is built on a backbone of airborne research that is now collapsing. Restoring the nation's airborne research program is a key prerequisite for linking the Earth sciences to emerging societal objectives and for the restoration of international leadership in higher education in the United States.

The airborne programs at NASA and NOAA are in transition from conventional aircraft to unmanned aerial vehicles (UAVs). UAVs have the potential to revolutionize suborbital remote and *in situ* sensing with their increased range and loiter time, and their ability to penetrate hazardous environments. However, issues with avionics software, flights over populated regions, high cost, and reliability have thus far limited UAVs to controlled demonstration missions. In the transition to future wide deployment of UAVs, conventional aircraft will continue to be the mainstay of the suborbital aircraft program—they are currently more reliable and more cost effective to use. The committee notes that the current neglect of conventional aircraft program in favor of UAV development has hindered scientific research; its recommendations below point towards a strengthened and balanced program of conventional and UAV aircraft.

Recommendation: Critical surface-based (land and oceans) 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.

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.

Observations of Human Impacts

Human influences on the Earth are apparent on all spatial and temporal scales. Thus, an effective Earth information system requires an enhanced focus on observing and understanding the impact of humans, the influence and evolution of the built environment, and the study of demographic and economic issues. For instance, space-derived information on urban areas can provide a platform for fruitful interdisciplinary collaboration among Earth scientists, social scientists (e.g., urban planners, demographers, and economic geographers), and other users in the applications community. Data on the geographic "footprint" of urban settlements, identification of intra-urban land-use classes, and changes in these characteristics over time are required to facilitate the study of urban population dynamics and composition, and thereby to improve the representation of human-modified landscapes in physical and ecological process models. Because of the rapid growth in urban areas, particularly in the developing world where there are few alternative sources of information on urban extent and land cover, these observations are needed to understand a growing source of anthropogenic forces on regional weather and climate, air and water quality, and ecosystems, and to apply this understanding to protect society and manage natural resources.

Recommendation: Earth system observations should be accompanied by a complementary system of observations of human activities and their effects on Earth.

TURNING OBSERVATIONS INTO KNOWLEDGE AND INFORMATION

There are many steps and pathways necessary to turn observations into quantitative information for use by scientific researchers and societal decision-makers. A central theme of this report is that space-based observation of the planet must address important societal needs—there needs to be a closer linkage to providing real benefits. In order to meet important needs, we need to improve our ability to extract information coherently from multiple observations and sensors, and address the already well-known, challenges of data and information management. Observations without analysis, interpretation and application are sterile, and hence it is crucial to ensure the vitality of research, analysis, and modeling programs.

Consideration of Societal Benefits and Applications

Chapter 5 (*Earth Science Applications and Societal Benefits*) in Part III discusses a number of important aspects of the process of realizing societal benefits from Earth observations through scientific research and application development. These include (1) establishing mechanisms for including priorities of the applications community in space-based missions, (2) considering studies of the value and benefits of Earth observations published in the social sciences literature, (3) creating closer institutional relationships between the science and applications (user) communities, (4) having easy availability to observations and products derived from observations by the broad user community, and (5) educating and training new users of Earth data and information, as well as facilitating the creation of a scientifically-informed and literate citizenry. Meeting these objectives will require a greater involvement of social scientists (e.g., development policy analysts, communication researchers, anthropologists, environmental economists) throughout the entire mission lifecycle, in order to make certain societal needs are appropriately considered during the design process, and to ensure societal benefits are derived from the implemented observations. Consequently, the committee recommends:\

Recommendation: Socioeconomic factors should be considered the planning and implementation of Earth observation missions and in developing the Earth Information System.

Deriving Data from Multiple Observations and Sensors

Observations must resolve appropriate temporal and spatial scales, which depend on the nature of the processes and the scientific questions that are posed. Simply specifying a measurement is not sufficient, and thorough analyses are required to estimate both measurement (e.g., noise in the sensor) and sampling errors (which are related to the sampling characteristics of the sensor and geophysical variability). Such considerations imply that many Earth science questions and applications require a suite of platforms in different orbits. Merged data products from different sensors (in different orbits or with different spectral characteristics) often overcome weaknesses that are present in a single-sensor approach. For example, infrared sensors can provide high spatial resolution measurements of SST, but they cannot make measurements in the presence of clouds. On the other hand, microwave sensors can "see" through clouds, but with much lower spatial resolution. Combining these systems in a rigorous statistical manner yields a much higher quality field of global SST.[8] Appendix C provides additional examples of how observations of the same variable (e.g., temperature) by different technologies (e.g., infrared, microwave,

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[8] Richard W. Reynolds, Thomas M. Smith, Chunying Liu, Dudley B. Chelton, Kenneth S. Casey, and Michael G. Schlax, "Daily High-resolution Blended Analyses for Sea Surface Temperature," manuscript in preparation.

and GPS) can be combined through four-dimensional variational data assimilation (4D-VAR) to produce analyses of the variable that are more accurate than the original observations alone.

Another emerging source of data is from the commercial sector. In the past, a program of Earth observations was associated almost exclusively with government-managed or government-sponsored projects. Today, commercial sources of Earth information are rapidly increasing in availability and scope. Commercial satellite systems now provide viable sources for high-resolution Earth imagery, and commercial remote sensing companies have greatly expanded their offerings. An important example is the emerging Internet geospatial browsers and web portals, best exemplified by Google Earth and Microsoft Virtual Earth. The new technologies revolutionize our ability to communicate Earth information to consumers, to share among diverse groups, and to receive feedback from the end-users of Earth information. Much of this capability is available for free. A long-term plan for Earth observations and information needs to account for these sources, as they promise to reduce the cost of Earth observation as well as introduce new and different means for looking at Earth.

In reviewing progress in obtaining Earth observations by commercial data providers to determine the potential applicability to the decadal plan, the committee sought input from several organizations responsible for providing commercial data covering both space-borne and airborne sources.[9] The detailed and thoughtful responses indicated a clear expectation that the field will evolve rapidly over the next decade. Both space-borne and aerial data sources will introduce imagery with increasingly fine spatial resolution and significant improvements in geolocation accuracy. Prices are expected to drop as the number of sources proliferates. Space-borne systems will provide enhanced spectral capability, with the possibility that hyperspectral data could become available from commercial sources. Constellations of imaging satellites, designed to reduce revisit intervals, will be launched. Radar imagery will become widely available, with highly-accurate global Digital Elevation Models representing one product. Much of the demand for this imagery will come from rapidly-emerging consumer geospatial internet applications, but the scientific community should also be able to take advantage of these datasets to complement other observing systems. Nevertheless, most of what is important scientifically will not be provided in the foreseeable future by commercial providers. Commercial sources should be viewed as an important and high-leverage adjunct to government systems, not as a general replacement.

New data sources from satellites may reduce the need for conventional observations, or from earlier satellite systems. In a cost-constrained environment, continued increase in observational systems cannot be supported, and in fact may not be necessary as more effective systems can replace older, less effective ones. Thus a systematic and continuous evaluation and assessment of the appropriate mix of global observations is necessary:

Recommendation: In order to evolve the global observing system in a cost-effective way to meet broad scientific and societal objectives and to extract maximum useful information from multiple observations and/or sensors, teams of experts should be formed to focus on providing comprehensive data sets that combine measurements from multiple sensors. These teams should consider assimilation of data from all sources, including commercial providers and international partners.

Data and Information Management

Earth observation is a data-rich endeavor involving processing, archiving, and distributing vast amounts of data and information. To achieve the benefits of Earth observations recommended in this

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[9] Responses were received from GeoEye, a provider of space borne imagery, and Management Association for Private Photogrametric Surveyors (MAPPS), an organization that represents both space-borne and airborne commercial imagery providers.

Report, support must be provided to the full range of data processing, analysis, archiving, and distribution for all space missions (see Chapter 5). At the same time, these data must be made easily and affordably available to users to support research and applications. The rapidly-emerging geospatial Internet promises new ways both to store and distribute Earth-related information and may provide opportunities to enhance the archiving and distribution of scientific information.[10]

The challenges of data archiving and access have been discussed in many previous reports from the NRC. The report, *Government Data Centers: Meeting Increasing Demands* (NRC, 2003a), focused on technological approaches that could enhance the ability of environmental data centers to deal with increasing data volume and user demands, and improve the ability of users to find and use information held in data centers. The more recent NRC report, *Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond* (NRC, 2004b), focused on the end-to-end utilization of environmental satellite data by characterizing the links from the sources of raw data to the end requirements of various user groups.

Because of the importance of a complete and effective data and information management system to the success of space-borne missions, the committee recommends:

Recommendation: 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.

Research and Analysis

A careful review of important scientific advances in the Earth sciences over the past years, particularly for those scientific developments most directly linked to societal decisions (Montreal Protocol; hurricane forecasting; toxicity studies of nitrate, sulfate, and heavy metal emission; earthquake forecasting; mechanistic coupling between dynamics, radiation, and chemistry within the climate system; etc.) reveals the central importance of the NASA Research and Analysis (R&A) programs to the national effort. In fact, U.S. scientific leadership, vitality, and technical agility rests directly on the on the nation's R&A; moreover, these programs are essential to the education of graduate students in the nation's universities that will become next generation of Earth scientists.[11] R&A studies enable conversion of raw instrument data into useful fields of geophysical variables and are a critical component of the research required to convert data analyses to trends, to understand processes, and to improve models. Without adequate R&A, the large, expensive, and complex tasks of acquiring, processing, and archiving geophysical data would be essentially wasted. Strong research and analysis programs in NASA, NSF, NOAA, USGS, and other agencies are crucial to realize the benefits from Earth observations. In its Interim Report, the committee expressed concern regarding the consequences of reductions in the level of support NASA was providing to its Earth observation R&A programs.[12] This concern has only increased as the mission plan summarized in Chapter 2 assumes a strengthened research and analysis program—one that is commensurate with current needs and those anticipated as the mission plan is executed. Thus, the committee makes the following recommendation:

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[10] See, for example, presentations at the NOAA Data and Information Users' Workshop, May 11-13, 2005, available at < http://www.ncdc.noaa.gov/oa/usrswkshp/index.html#report>.

[11] See National Research Council, *Earth Observations from Space: History, Promise, and Reality* (Executive Summary), National Academy Press, Washington, D.C., 1995.

[12] Interim Report, page ES-7.

Recommendation: 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 each mission as well as mission-specific operations and data analysis. These R&A lines should be protected within the missions and not used as mission reserves to cover cost growth on the hardware side.

Modeling

The complexity of the Earth system means that few problems of significance can be solved analytically or from observations alone. The tremendous advances in weather prediction, largely as a result of steadily-improving models, satellite data, and advanced data assimilation techniques (Box 3.4; Uppala et al., 2005; and Appendix C), provide a tangible example; such predictions are now made almost entirely on the basis of computational models. In fact, Uppala et al. (2005) concluded that improving models and data assimilation, including higher model resolution made possible by increasing computer power, have been the main reason for improving global weather predictions from 1980 to present. As our quest for knowledge becomes increasingly demanding and detailed, computational modeling and model-based analyses will play an ever-more central role in creating Earth knowledge and making practical predictions. Complete models of the Earth system must be developed along with advanced data assimilation techniques that can incorporate all observations into the model to produce consistent four-dimensional data sets for research and operations. Like investments in R&A, support for modeling, data assimilation, and advanced computation must be commensurate with the proposed observational systems. Accordingly, the committee makes the following recommendation:

Recommendation: 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.

BOX 3.4 THE WEATHER PREDICTION PARADIGM AND USE OF EARTH OBSERVATIONS

Numerical weather prediction (NWP) models have been the primary basis for weather forecasts for time periods beyond a day for many years. The models depend critically upon observations for their initial conditions. The earliest models in the 1960s and 1970s relied almost entirely on *in situ* observations of four traditional atmospheric variables—temperature, pressure, winds, and water vapor—obtained primarily by weather balloons, aircraft, ships, and surface observing stations over land. These observations were generally made and used in the models at 12-hour intervals (00 UTC and 12 UTC). The relatively few observations made at other times were generally not used at all in the models.

The earliest Earth observing satellites were developed primarily to improve weather forecasts. Throughout the 1960s and 1970s, although the visible and infrared imagery from satellites helped forecasters for short-term forecasts, quantitative satellite data like infrared and microwave radiances had little positive impact on NWP models, and, in fact, actually degraded the forecasts in many cases. This was because modelers were trying to convert the satellite observations (e.g., radiances) to the conventional observations (e.g., temperature and water vapor). By the 1990s, however, researchers had developed powerful new methods to use radiances and other non-traditional observations such as radar backscatter measurements in models through increasingly sophisticated *data assimilation* techniques, based on rigorous mathematical and physical principles (Appendix C). These methods also allowed models to effectively use the many satellite observations that were made throughout the day, rather than only those at two fixed times.

Over the decades of the 1980s and 1990s, and continuing today, the increasing number and types of global satellite observations, the improving methods of assimilating the many diverse data and improved models have been responsible for a remarkable increase in model forecast accuracy, which in turn has led to steadily improving weather forecasts delivered to the users. Figure 3.2 shows the monthly moving average of the correlations between forecast and observed anomalies of the 500 hPa height fields (essentially the pressure fields at about 5.5 km or 18,000 ft in the atmosphere) in 3, 5, 7, and 10 day forecasts. Forecasting these anomalies accurately is essential in forecasting weather; the higher the correlation, the better the forecast. Numerical forecasts with correlations of 60% or higher are generally considered useful. The top part of each band refers to the accuracy of the Northern Hemisphere (NH) forecasts; the bottom part of each band refers to the Southern Hemisphere (SH) forecasts.

Figure 3.2 shows a number of interesting and important features. First, in 1981 the NH forecasts were significantly better than those in the SH. This is because there were (and still are) many more traditional observations in the NH. With time, the forecasts have steadily improved, so that the 5-day forecast today in the NH is as accurate as the 3-day forecast was in 1981. This improvement has occurred in spite of the fact that the number of conventional upper-air observations has actually decreased over this time (Uppala et al., 2005).

Figure 3.2 also shows that the difference between the accuracy of the forecasts in the two hemispheres has become much less over time, and in fact there is little difference today because of satellite observations, which cover the two hemispheres equally.

The paradigm of assimilating observations of different geophysical variables made from many instruments and platforms into mathematically and physically based numerical models has been responsible for the steady improvement in weather forecasts. This paradigm is now increasingly used to study the oceans, hydrologic processes, air pollution (chemical weather), and ionospheric circulations and storms (space weather). It is also being used to create accurate and dynamically-consistent global data sets of the atmosphere and oceans, which are valuable for climate monitoring and research studies. It provides a scientifically-based method to combine all available sources of information from current observations and observations in the recent past, to produce the best possible estimate of the state of the atmosphere, ocean, and land surfaces. Many diverse and independent observations from space, over the entire Earth, are an essential component of this powerful paradigm.

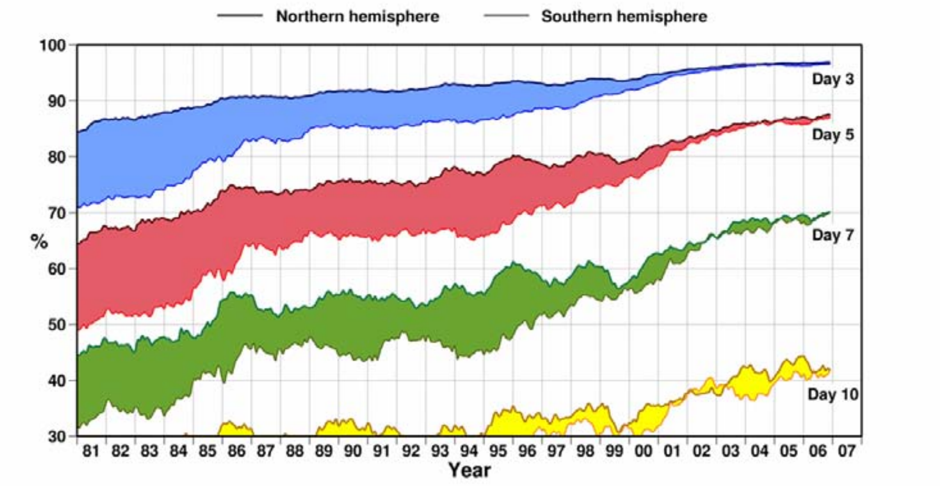

FIGURE 3.2 The correlation between 500 hPa anomalies (atmospheric features at about 5.5 km or 18,000 ft) in numerical weather prediction model forecasts at 3, 5, 7, and 10 days from the European Centre for Medium-Range Weather Forecasts (ECMWF). Higher correlations denote more accurate forecasts. Please see text for further interpretation. SOURCE: Courtesy of the European Centre for Medium-range Weather Forecasts.

SUSTAINING THE KNOWLEDGE AND INFORMATION SYSTEM

A successful Earth information system needs to be planned and implemented around long-term strategies that encompass the life cycle 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. And, while any successful program depends upon individuals in leadership positions, the process must be resilient to changes in leadership that are inevitable over long periods of time. In this section we highlight the needs for continual planning of the satellite observing program in the face of funding and technology uncertainties, for transitioning select measurements from research to operations and applications, and for training the next generation of Earth information specialists.

Planning for Uncertainty: Reviewing and Revising Plans

The missions recommended in Chapter 2, together with other national and international missions, will provide the necessary space-based observational foundation for the coming decade of Earth information needs. However, these missions were developed against a backdrop of programmatic constraints and available resources that are expected to evolve over time. Budgets occasionally increase, bringing opportunities to enhance the program. They also decline, forcing cuts and requiring re-prioritization. Technological advances are difficult to predict, and some missions that are dependent on a new technology may find that they are simply not ready to fly on the originally planned schedule. Therefore, all programs should be reviewed regularly for potential problems as well as new opportunities**,** *by an external, independent, and community-based advisory body.*

Given the challenges of any high technology program and the experience of cost growth in executing other decadal surveys, the committee has formulated a set of Programmatic Decision Strategies and Rules (Table 3.1) which should be considered, in consultation with the advisory body, when restructuring becomes necessary or desirable. More broadly, these strategies and rules are intended for overall programmatic management.

The programmatic decision strategies summarized in Table 3.1 are derived from principles discussed in a number of previous NRC studies. Regarding the maintenance of overall program integrity, an effective and robust Earth observation program must be balanced in a number of important ways (NRC, 2006b):

- *Balancing Scientific Disciplines* – Earth system science depends on a broad range of scientific disciplines and ongoing progress in all areas of importance. The very nature of scientific enquiry and discovery means that there will be surprises, which often come from unexpected and unplanned places. What seems to be most important in one year may be superseded by another great challenge or opportunity in the next.[13] Furthermore, multidisciplinary and interdisciplinary research and cooperation can yield transformative discoveries and pay huge and unforeseen dividends.[14] Thus, while priorities must be made, it is vitally important to ensure the health of all the disciplines of Earth science.

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[13] As just one example, consider that 10-15 years ago, no one anticipated that tides and their interaction with ocean bathymetry would be important for explaining mixing processes in climate models.

[14] A notable example is the use of the Global Positioning System (GPS) for applications in solid-Earth and atmospheric sciences.

TABLE 3.1 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 large 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.

- *Balancing Mission Size* – Prior NRC reports (NRC, 2000b; NRC 2006a,b) have concluded that ensuring a balance of facility class (large), medium, and small missions is important to 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 (e.g., EOS or NPOESS class) toward smaller missions to increase programmatic robustness.
- *Balancing Technology Maturity* – Tomorrow's missions are built on the foundation of today's technology programs. Even in a constrained budget, maintaining innovation in instrument and other hardware development goes hand-in-hand with scientific advance. By starting several missions with extended Phase A studies, one can avoid technology difficulties that can lead to roadblocks and worse. Missions should not move forward until the Technological Readiness Level is appropriate. This may require that a mission move out of the queue until the instrumentation issues are in hand. Addressing such technology readiness issues must be accomplished without incurring substantial costs in maintaining the temporarily idled mission engineering and operations teams.
- *Balancing Observations with Analysis and Modeling* – Observations are often ineffective unless the tools exist to analyze and understand them. An appropriate balance is needed between resources allocated toward observations and those supporting analysis and modeling and the associated computer power and related cyber infrastructure. This is related to the importance of Research and Analysis expressed in Section 3.3 and the central role of models in improving forecasts (Box 3.4)
- *Balancing Stability and Adaptability* – An effective Earth information system requires both long-term stability and short-term adaptability. Long-term stability ensures that the most important programs are carried through despite inevitable budgetary and programmatic pressures. Adaptability ensures that the program retains sufficient flexibility to respond to evolving scientific and societal needs, new insights, and unforeseen technological capabilities. Reconciling these competing requirements is difficult and requires strong leadership and management, continuous review and advice by independent bodies, and a modest budget reserve to allow flexibility to make changes as warranted by changing conditions.

As this new program on Earth observations, analysis, and applications goes forward, NASA, NOAA, USGS, and their partners should maintain a set of balances that cut across various dimensions of Earth sciences. These balances are essential for developing, implementing, and adjusting as necessary a healthy Earth Sciences and Applications program. In an inherently interdisciplinary and changing field, there is great strength in a diversity of ideas, observations, and applications.

Leveraging of international efforts has been a consistent focus of NASA's research program in the past and likely needs to play a more prominent role in the future. There are many examples of successful international missions that share technologies and costs. For example, the Tropical Rainfall Measurement Mission (TRMM), a partnership between Japan and the U.S., produced the first rainfall estimates from a radar in space (NRC, 2006c). The Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) mission, a joint Taiwan-U.S. mission flew the first constellation of radio occultation receivers in space, producing near real-time atmospheric profiles for operations and research (Cheng et al., 2006). The European MetOp satellite, launched on October 19, 2006, carries several instruments developed by the United States.[15] Additional examples may be found in the

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[15] MetOp incorporates a set of "heritage" instruments provided by the United States: AVHRR radiometer for global imagery, the AMSU-A microwave sounder, the HIRS infrared sounder, an advanced Argos data collection system, a Search & Rescue package and the SEM-2 spectrometer to monitor charged particle flux in space. See <http://www.esa.int/esaLP/SEMV68L8IOE_LPmetop_0.html>.

Committee on Earth Observation Satellites (CEOS) handbook.[16] Thus international collaborations, including full and open sharing of data, should be encouraged and explored wherever possible.

On February 16, 2005, 61 countries agreed to a 10-year plan to implement a "Global Earth Observation System of Systems" (GEOSS).[17] Nearly 40 international organizations also supported the creation of this global network. GEOSS is the most recent attempt to realize the promise of international collaboration.[18] Finally, we note again the importance of leveraging international activities on the sequencing of missions (Table 3.1).

At the beginning of this section, this committee stated that the missions recommended in Chapter 2, together with other national and international missions, would provide the necessary space-based observational foundation for the coming decade of Earth information needs. The committee recognizes that achieving this program will be challenging, and we set forth (Table 3.1) suggested strategies and rules for overall programmatic management. We conclude with a recommendation:

Recommendation: A formal interagency planning and review process should be put into place that focuses on effectively implementing the committee recommendations and sustaining and building the knowledge and information system for the next decade and beyond.

Investing in People through Education and Training

The training of future scientists needed to interpret observations, and who will turn the measurements into knowledge and information is exceedingly important in the framework of this report. The need for such training points to the importance of a continuous and stable stream of funding for universities and government researchers. The committee noted with interest a recent Interim Report of Committee on Meeting the Workforce Needs for the National Vision for Space Exploration (Box 3.5).[19]

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[16] Available online at: <http://www.eohandbook.com/>.

[17] See, "Global Earth System of Systems" at <http://www.epa.gov/geoss/>.

[18] GEOSS grew out of the U.S.-led 2003 Earth Summit, whose objectives were to: 1. Promote the development of a comprehensive, coordinated, and sustained Earth observation system or systems among governments and the international community to understand and address global environmental and economic challenges; and 2. Begin a process to develop a conceptual framework and implementation plan for building this comprehensive, coordinated, and sustained Earth observation system or systems. See, "Earth Observation Summit," available at <http://www.earthobservationsummit.gov/index.html>.

[19] National Research Council, *Issues Affecting the Future of the U.S. Space Science and Engineering Workforce—Interim Report*, The National Academies Press, Washington, D.C., 2006.

BOX 3.5 RECOMMENDATIONS OF THE INTERIM REPORT OF THE NRC COMMITTEE ON MEETING THE WORKFORCE NEEDS FOR THE NATIONAL VISION FOR SPACE EXPLORATION

1. NASA should develop a workforce strategy for ensuring that it is able to target, attract, train, and retain the skilled personnel necessary to implement the space exploration vision and conduct its other missions in the next 5 to 15 years. The agency's priority to date has been to focus on short-term issues such as addressing the problem of uncovered capacity (i.e., workers for whom the agency has no current work).[20] However, NASA soon might be facing problems of expanding needs or uncovered capacity in other areas and at other centers. Therefore, it is important to develop policies and procedures to anticipate these problems before they occur.
2. NASA should adopt innovative methods of attracting and retaining its required personnel and should obtain the necessary flexibility in hiring and reduction-in-force procedures, as well as transfers and training, to enable it to acquire the people it needs. NASA should work closely with the DOD to initiate training programs similar to those that the DOD has initiated, or otherwise participate actively in the DOD programs.
3. NASA should expand and enhance agency-wide training and mentorship programs, including opportunities for developing hands-on experience, for its most vital required skill sets, such as systems engineering. This effort should include coordination with DOD training programs and more use of exchange programs with industry and academia.

The Committee on Meeting the Workforce Needs for the National Vision for Space Exploration is examining the role that universities play in supplying, training, and supplementing NASA's workforce. Part of the committee's charge is to consider the role that universities can play in providing hands-on space mission training of the workforce, including the value of carrying out small space missions at universities. We believe this report will also be of value to the Science Mission Directorate and above copy several of the recommendations of this committee's Interim Report.

As described in Part III Chapter 5, an essential component of a successful Earth observation program is effective and extensive use of data and information by the scientific and user communities. 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. Education and training for smaller, more specialized communities can be accomplished through symposia and workshops, while larger audiences can be accommodated through computer-aided distance learning. It is particularly important to begin education and training programs early so that the user community is ready when new types of data become available, thus maximizing their value during the life of each

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[20] "Uncovered capacity" is NASA's term for a serious problem with workers for whom the agency has no current work. When NASA cuts programs or reduces budgets, it is left with civil service personnel who may no longer have work to perform. Unlike industry, NASA cannot simply lay off these unneeded workers, but must conform to a complex set of civil service rules. Normally the agency will have some uncovered capacity in its workforce, but in 2005 and into 2006 this number was identified as constituting a significant percentage of its total workforce. During that time NASA was also forbidden by law from conducting a reduction in force, or RIF, to reduce its workforce. As a result, the agency exercised alternative methods to reduce this excess workforce and cut the excess capacity in half by January 2006. The cumulative effects of paying for unnecessary employees can damage the agency in a number of ways, including diversion of tight program funding and the use of poorly qualified employees for work that might otherwise be performed by contractors.

space-based sensor. Finally, science educators in the K-12 and university communities need to learn about new observing systems so that they may integrate this information into their curricula to improve scientific literacy of future scientists, teachers, and the public as a whole. Thus, the committee makes the following recommendation:

Recommendation: NASA, NOAA, and USGS 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.

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Part II:
Mission Summaries

In Chapter 2 of this report, the committee describes the observational portion of a strategy for obtaining an integrated set of space-based measurements in the next decade. The 17[1] missions summarized in this chapter (see tables below) form the centerpiece of this strategy. Here, in Part II of this report, the committee provides a more detailed discussion of each of the missions. Each mission summary also contains references to the particular Panel chapters in which the missions are discussed, as well as the index numbers that point to related RFI responses.[2]

TABLE 2.1 Launch, orbit, and instrument specifications for the recommended NOAA missions. Shade colors denote mission cost categories as estimated by the NRC ESAS committee (see Box 2-2). Green and blue shadings represent medium ($300 million to $600 million) and small (<$300 million) missions, respectively.

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost Estimate
Timeframe 2010 - 2013—Missions listed by cost				
CLARREO (NOAA portion)	Solar and Earth radiation characteristics for understanding climate forcing	LEO, SSO	Broadband radiometer	$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	MEO, SSO	Backscatter radar	$350 M

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[1] Note that CLARREO is listed twice as its instruments are directed for support by both NASA and NOAA.

[2] A complete index of RFI responses is provided in Appendix E. Full-text versions of the responses are available on the compact disc that accompanies this report.

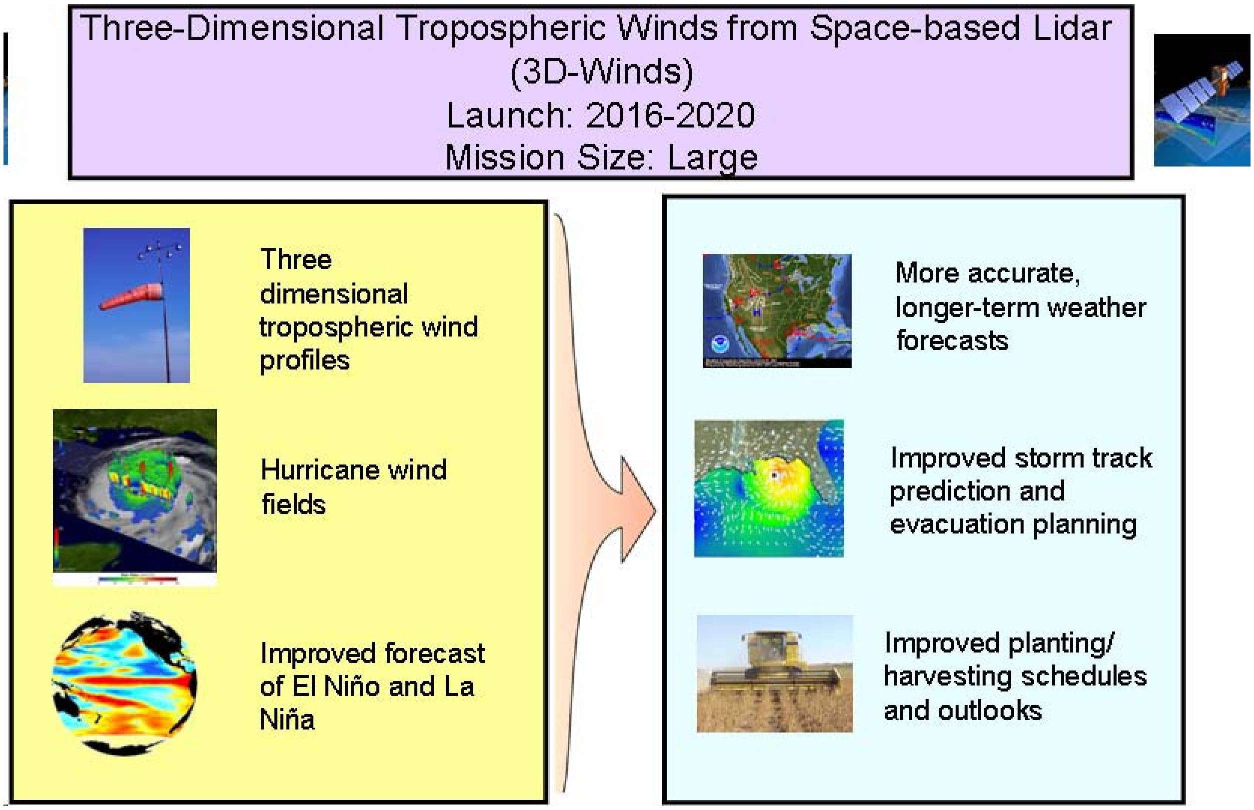
TABLE 2.2 Launch, orbit, and instrument specifications for the recommended NASA missions. Shade colors denote mission cost categories as estimated by the NRC ESAS committee. Pink, green, and blue shadings represent large ($600 million to $900), medium ($300 million to $600 million), and small (<$300 million) missions, respectively. Missions are listed in order of ascending cost within each launch timeframe.

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

4
Summaries of Recommended Missions

Three-Dimensional Tropospheric Winds from Space-based Lidar (3D-Winds)



Three-Dimensional Tropospheric Winds from Space-based Lidar (3D-Winds)
Launch: 2016-2020
Mission Size: Large

- Three dimensional tropospheric wind profiles
- Hurricane wind fields
- Improved forecast of El Niño and La Niña

- More accurate, longer-term weather forecasts
- Improved storm track prediction and evacuation planning
- Improved planting/ harvesting schedules and outlooks

More accurate, more reliable, and longer-term weather forecasts, driven by fundamentally improved tropospheric wind observations from space, would have a direct and measurable societal and economic impact. Tropospheric winds are the number one unmet measurement objective for improving weather forecasts.

Public safety through disaster mitigation will also benefit from improved forecasts of extreme weather events. For example, hurricanes are generally steered by tropospheric winds, and the vertical shear of those winds is often responsible for increasing their intensity. Public confidence in hurricane warnings will increase as forecasts get better. Therefore, a direct application and benefit of improved three-dimensional tropospheric wind observations from space is a superior description of hurricane wind fields, which will result in substantial numbers of lives saved.. Similar benefits are expected from improved forecasts of severe weather outbreaks, tornadic storms, floods, and coastal high-wind events.

Background: The proper specification and analysis of tropospheric winds is an important prerequisite to accurate numerical weather prediction (NWP). Even with the recent advances in the assimilation of radiances, wind is still a critical parameter for data assimilation and NWP because of the unique role it plays in specifying the initial potential vorticity, an essential requirement for accurate forecasting. Scientific applications are severely limited by the lack of directly-measured three-dimensional wind information over the oceans, the tropics, the polar regions, and the Southern Hemisphere, where other meteorological observations are scarce. To date, large analysis uncertainties remain over wide areas of the globe, especially for the three-dimensional tropospheric wind field. More accurate, more reliable, and longer-term weather forecasts, driven by fundamentally improved wind observations from space, would have a direct and measurable societal and economic impact.

Scientific Objectives: This space-based mission is designed to provide three-dimensional tropospheric winds on the global scale under a variety of aerosol loading conditions. Because wind is ultimately related to the transport of all atmospheric constituents, its measurement is crucial to improve our understanding of sources and sinks of constituents such as atmospheric water. The transport of water vapor is an essential component needed to close the regional hydrologic cycles that should enable scientific advances in understanding of El Niño, monsoons, and the flow of tropical moisture to the U.S. Reliable global analyses of three-dimensional tropospheric winds are needed to improve the depiction of atmospheric dynamics, transport of air pollution, and climate processes. Finally, the value of accurate wind measurements in day-to-day weather forecasting is well-known. For example, the tracks of tropical cyclones are modulated by environmental wind fields that will be better analyzed and forecasted with the assimilation of these newly-available wind profiles.

Mission and Payload: The Weather Panel determined that a Hybrid Doppler Wind Lidar (HDWL) in low Earth orbit (LEO) could make a transformational impact on global tropospheric wind analyses.

The HDWL is a combination of two separate DWL systems (coherent and non-coherent) operating in different wavelength ranges that have distinctly different, but complementary, measurement advantages and disadvantages. One DWL system would be based on a coherent Doppler lidar approach using a 2 μm laser transmitter and a coherent detection system. This type of system has been used extensively in ground-based Doppler lidars and more recently in a few airborne lidar systems. Because the operational wavelength of this system is in the near-infrared, this type of system is particularly sensitive to wind measurements in the presence of aerosols, such as in the planetary boundary layer (PBL) or in aerosol-rich layers in the free troposphere resulting from biomass burning plumes or clouds. It has low sensitivity in regions with low aerosol loading frequently found in the free troposphere and above the tropopause. The second type of DWL that would be part of the HDWL operates at ultraviolet wavelengths and uses the non-coherent detection of the molecular Doppler shifts to enable wind measurements in the "clean" air regions. The combination of these two DWL systems into a HDWL will allow for wind measurements to be made across most tropospheric and stratospheric conditions.

Due to the complexity of the technology associated with a HDWL, the Panel strongly recommends an aggressive program early on to address the high-risk components of the instrument package, and then design, build, aircraft-test, and ultimately conduct space-based flights of a prototype HDWL. This program should also complement and leverage where possible the work being performed by ESA with a non-coherent lidar system. The Panel recommended a phased development of the HDWL mission with the following approach*: Stage 1:* Design, develop and demonstrate a prototype HDWL system capable of global wind measurements to meet demonstration requirements that are somewhat reduced from operational threshold requirements. All of the critical laser, receiver, detector, and control technologies will be tested in the demonstration HDWL mission. *Stage II:* Launch of a HDWL system that would meet fully-operational threshold tropospheric wind measurement requirements. This mission would represent a transformational change in the way global wind data is obtained to be assimilated into the latest NWP models.

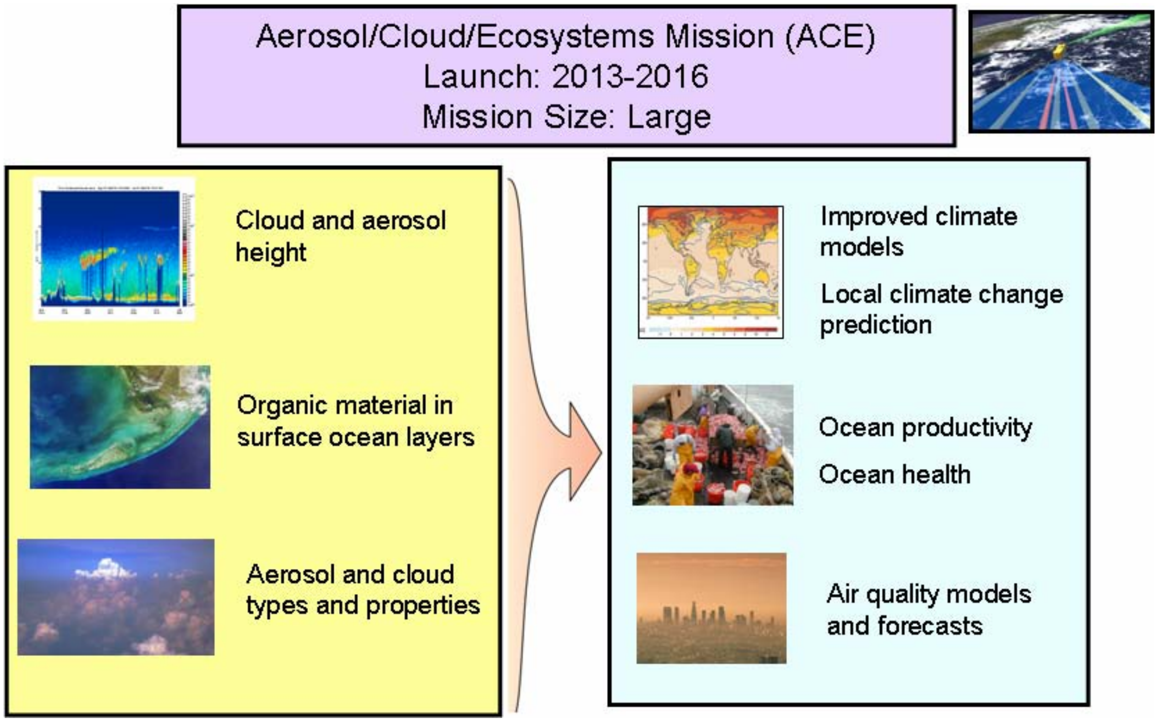
Cost: ~$650M (Stage I demonstration HDWL mission)

Schedule: Stage I: Space demonstration of a prototype HDWL in LEO to take place as early as 2016. Stage II: It is expected that a fully operational HDWL system could be launched as early as 2022.

Further Discussion: Weather Science and Applications (Chapter 10) Section 10.3.1

Related RFI(s): 28, 29, 78

Aerosol/Cloud/Ecosystems Mission (ACE)



The primary goal of the Aerosol/Cloud/Ecosystem Mission (ACE) is to reduce the uncertainty of climate forcing in aerosol-cloud interactions and ocean ecosystem CO_2 uptake. Aerosol-cloud interaction is the largest uncertainty in current climate models. Aerosols can make clouds brighter and affect their formation. Aerosols can also affect cloud precipitation and have been attributed to decreased rainfall in the Mediterranean. The results of this mission will narrow the uncertainty in climate predictions and improve the capability of models to provide more precise local predictions of climate change including changes in rainfall. The ACE aerosol measurements can also be assimilated into air quality models to provide improved air quality forecasts. The ocean ecosystem measurements will provide information on uptake of carbon dioxide by phytoplankton and improve our estimates of the ocean CO_2 sink. As CO_2 increases, the oceans will acidify which impacts the whole food chain including coral reef formation. This mission can assess changes in productivity of pelagic fishing zones and provide the early detection of harmful algal blooms. Benefits from this mission would include enabling the development of adaptation strategies to climate change, evaluating the consequences of increasing of greenhouse gases, enabling improved public health through early warning of pollution events and evaluation of impact of climate change on ocean ecosystems and food production.

Background: The largest uncertainties in global climate change prediction involve the role of aerosols and clouds in the Earth's radiation budget, and the impact of aerosols on the hydrological cycle. Aerosol climate forcing is similar in magnitude to CO_2 forcing, but the uncertainty is five times larger, an assessment that has not changed from the earlier IPCC reports. Among the reasons for the uncertainty is that aerosols have a short lifetime in the atmosphere and not all aerosols are alike. Aerosols also have a large impact on cloud formation (the indirect effect) and brightness, and this amplifies their importance to the climate system. Aerosols, and the clouds they affect, tend to increase the reflected solar radiation. Aerosols have likely masked some of the temperature rise associated with global warming. Both the NASA A-Train mission set and the planned ESA EarthCARE mission will provide early information on this problem. ACE is to provide significantly more data of a much higher quality than these predecessor missions. The higher quality is needed to reduce our uncertainty in cloud-aerosol interaction among the various types of aerosols and thus improve climate prediction models. ACE aerosol measurements would be NASA's specific contribution to an overall integrated aerosol measurement plan as envisioned in PARAGON (Bull. A. M. S, 2004). The need for an advanced aerosol-cloud mission has also been identified by a series of community workshops conducted by NASA during 2005 & 2006.

ACE will also be able to make next-generation pelagic ocean ecosystem measurements using the same set of instruments. The ocean is a rapid processor of carbon and a major uncertainty in the global carbon flux. The estimated ocean carbon uptake through its ecosystem is about as large as the total uncertainty in the carbon budget, and recent estimates from O_2/N_2 flux ratios suggest that the current estimates may be much more uncertain than previous believed. Carbon uptake by the ocean is influenced by climate change through changes in wind stress and salinity that produce a concomitant response in zones of upwelling, mixed layer depth, aeolian fertilization, the marine ecosystems and the export of carbon to marine depths.[3] Still uncertain is the global impact of ocean acidification as dissolved CO_2 content in ocean water continues to rises.

Science Objectives: The science goal of ACE is to reduce the uncertainty in climate forcing through two distinct processes described above. The first goal is to better constrain aerosol-cloud interaction. This goal is achieved by simultaneous measurement of aerosol and cloud properties by radar, lidar, polarimeter, and a multi-wavelength imager. This multi-instrument payload is needed because aerosols can either enhance or suppress cloud formation, depending on the aerosol type, and aerosol loading can reduce precipitation over continental wide areas. Since aerosols can be transported long distances, space-based assessment of this problem combined with ground-based measurement is the most scientifically-effective and cost-effective approach to quantitatively estimating the effect of aerosols on clouds. The second goal is to estimate the carbon uptake by ocean ecosystems through global measurements of organic material in the surface ocean layers. The oceans are a significant sink for atmospheric CO_2, and the oceans are acidifying as a result of CO_2 uptake. To better estimate the uptake of carbon and the change in the ocean food chain, we need to make improved measurements of organic carbon using multi-spectral measurements of the "ocean color." The ocean is a dark surface (except at the sun-glint) and reflecting solar radiation aerosols interfere with ocean color measurements, thus it appropriate that simultaneous aerosol measurements be made with ocean color measurements. The two objectives of aerosol and ocean color measurements are thus highly synergistic.

Mission and Payload: To avoid the sun-glint yet take maximum advantage of the reflected solar radiation, ACE will fly in a LEO, sun-synchronous early-afternoon orbit. The orbit altitude of 500-650 km will allow sufficient orbit lifetime yet is close enough to the surface that active sensors power requirements are not so high to limit the mission lifetime. The notional mission consists of four instruments: 1) a multi-beam cross-track dual wavelength lidar for measurement of cloud and aerosol heights and layer thickness; 2) a cross-track scanning cloud radar with channels at 94 GHz and possibly 34 GHz for cloud droplet size, glaciation height, and cloud height; 3) a highly accurate multiangle-multiwavelength polarimeter to measure cloud and aerosol properties (This instrument, unlike the Aerosol Polarimetry Sensor on Glory, would have a cross-track and along-track swath with ~1 km pixel size.); and 4) a multi-band cross-track visible/UV spectrometer with ~1 km pixel size, including Aqua MODIS, NPP VIIRS, and Aura OMI aerosol retrieval bands and additional bands for ocean color and dissolved organic matter. Additional use of the lidar for canopy height should be studied.

The core aerosol sensors are the polarimeter and the lidar – they provide aerosol properties and height. Additional aerosol information comes from the UV channels of the multi-band spectrometer. In order to determine impact on clouds, the cloud radar will determine the cloud droplet size, altitude of glaciation

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[3] Salinity and temperature both affect the solubility of CO_2 in seawater and hence the carbon uptake.

and estimate total cloud water. The radar, lidar and polarimeter are the primary cloud sensors; the polarimeter can also determine cloud droplet size. The primary ocean color sensor is the multi-band spectrometer with channels sensitive for chlorophyll absorption and dissolved organic matter. The UV bands in the spectrometer can also be used to determine aerosol type and allow for aerosol retrievals over bright surfaces. Aerosol information needed for the ocean color retrieval is derived from the polarimeter and lidar.

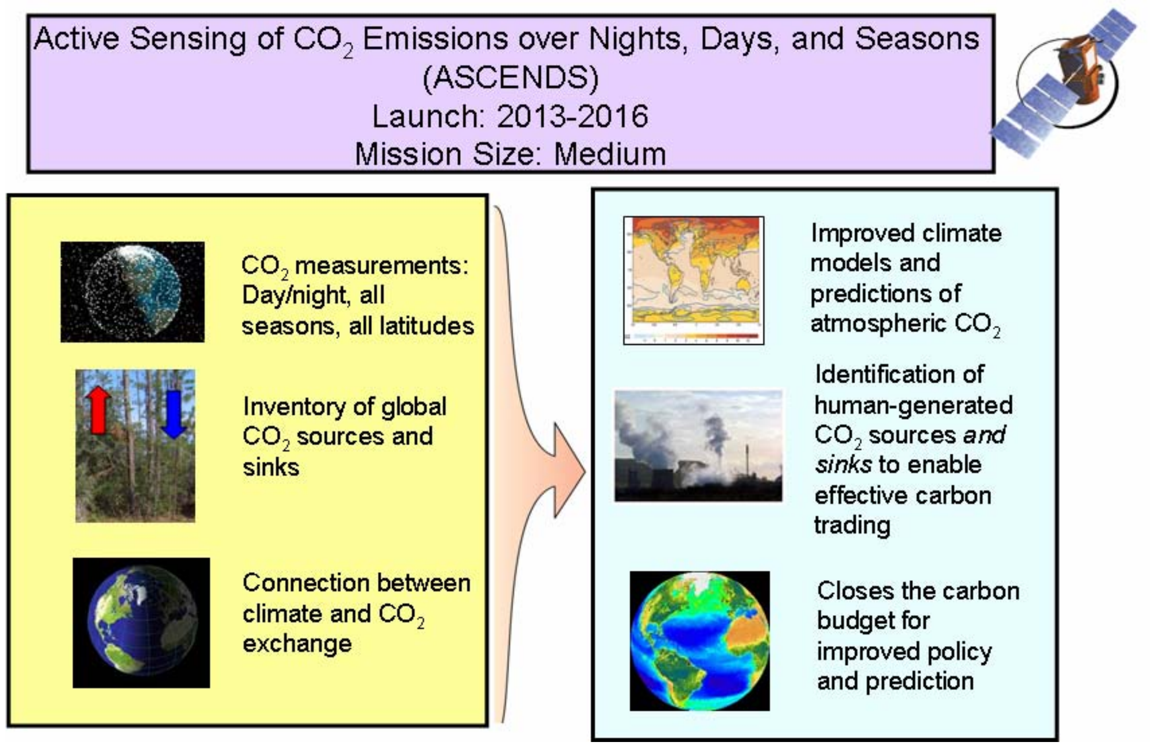
Mission Cost: ~$800M

Schedule: All of the instruments have some space heritage. Incremental technology development in lidars, radars, and polarimeters is needed to extend the capabilities for multi-beam and cross-track measurements. We expect such technology developments will support this mission by 2015-2016 if not earlier.

Further Discussion: Climate Change and Variability (Chapter 9) Sections 9.3.1.1, 9.3.2.2.1-2; Weather Science and Applications (Chapter 10) Sections 10.3.4 and 10.4.2, and Table 10.2; Land-Use, Ecosystems, and Biodiversity (Chapter 7) Section 7.5.6

Related RFI(s): 7, 21, 45, 81, 66, 86, 97, 102, 110, 88

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS)



Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
(ASCENDS)
Launch: 2013-2016
Mission Size: Medium

CO_2 measurements: Day/night, all seasons, all latitudes

Inventory of global CO_2 sources and sinks

Connection between climate and CO_2 exchange

Improved climate models and predictions of atmospheric CO_2

Identification of human-generated CO_2 sources *and sinks* to enable effective carbon trading

Closes the carbon budget for improved policy and prediction

The primary human activities contributing to the near 40% rise in atmospheric CO_2 since the middle of the last century are fossil fuel combustion and land-use change, primarily the clearing of forests for agricultural land. More than 50% of the CO_2 from fossil fuel combustion and land-use change has remained in the atmosphere with land and oceans having sequestered the non-airborne fraction in approximately equal proportions. However, the proportional balance between land and oceans varies in time and space. The current state of the science cannot account for the growth rate and interannual variations of atmospheric CO_2 with confidence. The variability of the rate of increase in the concentration of CO_2 in the atmosphere cannot be explained by the variability in fossil fuel use; rather it appears to primarily reflect changes in terrestrial ecosystems that are connected with large-scale weather and climate modes. The overall pattern is important, and we do not understand it. The geographic distribution of the land and ocean sources and sinks of CO_2 has likewise remained elusive. This uncertainty is also important. As nations seek to develop strategies to manage their carbon emissions and sequestration, the capacity to quantify the present-day *regional* carbon sources/sinks and to understand the underlying mechanisms are central to prediction of future levels of CO_2, and thereby, informed policy decisions, sequestration monitoring, and carbon trading.[4]

Background: Direct oceanic and terrestrial measurements of carbon and/or the flux of CO_2 are important but resource-intensive and hence sparse, and difficult to extrapolate in space and time. Space-based measurements of primary production and biomass are valuable and needed, and the problem of source-

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[4] Dilling L, Doney SC, Edmonds J, Gurney KR, Harriss R, Schimel D, Stephens B, Stokes G. 2003. The role of carbon cycle observations and knowledge in carbon management. *Annual Review of Environment and Resources* 28: 521-558 2003. Integrated Global Carbon Observing Strategy (IGOS): Carbon Theme Report, International Geosphere-Biosphere Programme (IGBP). US Climate Change Science Program (CCSP), 2003, available at http://www.climatescience.gov/; US Carbon Cycle Science Program (CCSP), 2004, available at http://www.carboncyclescience.gov/.

sink determination of CO_2 will be aided greatly by such measurements and studies, but it will not be resolved by this approach. There is, however, a different complementary approach. Since the atmosphere is a fast but incomplete mixer and integrator of spatially- and temporally-varying surface fluxes, the geographical distribution (e.g., spatial gradient) and temporal evolution of CO_2 in the atmosphere can be used to quantify surface fluxes.[5] The current set of direct *in situ* atmospheric observations is far too sparse for this determination; however, long term, accurate measurements of atmospheric CO_2 column measurements with global coverage would allow the determination and localization of CO_2 fluxes in time and space.[6] What is needed for space-borne measurements is a highly-precise global dataset for atmospheric CO_2 column measurements without seasonal, latitudinal, or diurnal bias, and it is possible with current technology to acquire this dataset with a space-borne sensor using multiple-wavelength laser absorption spectroscopy.

The first step in inferring ecosystem processes from atmospheric data is to separate photosynthesis and respiration: for this, diurnal sampling is required to observe nighttime concentrations resulting from respiration. Analyses of flux data shows that there is a vast difference in process information between one measurement per day and one day plus one night measurement, with a much smaller gain going to many observations per day.[7] It is also essential to separate physiological fluxes from biomass burning and fossil fuel use, which requires simultaneous measurement of an additional tracer, ideally carbon monoxide (CO).

A laser-based CO_2 mission is the logical next step after the launch of NASA's Orbiting Carbon Observatory (OCO),[8] which uses reflected sunlight, and it will directly benefit from the data assimilation procedures and calibration and validation infrastructure that will handle OCO data. In addition, it will be important to overlap the new measurements with OCO, and hence this mission needs to be launched in the 2013-2016 timeframe at the latest.

Scientific Objectives: The goal of Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission is to significantly enhance the understanding of the role of CO_2 in the global carbon cycle. The Mission Goal is addressed through three Science Objectives.

> ***Objective 1.*** Quantify global spatial distribution of atmospheric CO_2 on scales of weather models in the 2010-2020 era.
> ***Objective 2.*** Quantify current global spatial distribution of terrestrial and oceanic sources and sinks of CO_2 on 1 degree grids at weekly resolution.
> ***Objective 3.*** Provide a scientific basis for future projections of CO_2 sources and sinks through data-based process Earth System model enhancements.

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[5] Tans PP, Fung IY, Takahashi T. 1990. Observational Constraints on the Global Atmospheric CO_2 Budget. *Science* 247 (4949): 1431-1438. Monitoring Carbon From Space, Eos, Vol. 86, No. 41, 11 October 2005, pages 384-385.

[6] Baker, D.F., S. Doney, and D.S. Schimel, Variational data assimilation for atmospheric CO_2, *Tellus-B* (in press). Crisp D, Atlas RM, Breon FM, Brown LR, Burrows JP, Ciais P, Connor BJ, Doney SC, Fung IY, Jacob DJ, Miller CE, O'Brien D, Pawson S, Randerson JT, Rayner P, Salawitch RJ, Sander SP, Sen B, Stephens GL, Tans PP, Toon GC, Wennberg PO, Wofsy SC, Yung YL, Kuang Z, Chudasama B, Sprague G, Weiss B, Pollock R, Kenyon D, Schroll S 2004 The Orbiting Carbon Observatory (OCO) Mission. *Advances in Space Research* 34 (4)700-709.

[7] Sacks, W, D Schimel and R Monson. 2006. Coupling Between Carbon Cycling and Climate in a High-elevation, Subalpine Forest: A model-data Fusion Analysis. *Oecologia*, DOI 10.1007/s00442-006-0565-2.

[8] The Orbiting Carbon Observatory (OCO) is a NASA Earth System Science Pathfinder Project (ESSP) mission designed to make precise, time-dependent global measurements of atmospheric carbon dioxide (CO2) from an Earth orbiting satellite. OCO should begin operations in 2009. See description online at < http://oco.jpl.nasa.gov/>.

Mission and Payload: The Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) laser sounder mission, consists of simultaneous laser remote sensing of CO_2 and O_2, which is needed to convert CO_2 concentrations to mixing ratios. The precision of the mixing ratio needs to be measured 0.5 % of background (slightly less than 2 ppm) at 100 km horizontal length scale over land and 200 km over open oceans. Such a mission can provide: 1) full seasonal sampling to high latitudes, 2) day/night sampling, and 3) some ability to resolve (or weight) the altitude distribution of the CO_2 column measurement, particularly across the mid to lower troposphere. CO_2 lines are available in the 1.57 and 2.06 µm bands that minimize the effects of temperature errors. Lines in the 1.57 µm region are identified as potential candidates because of their relative insensitivity to temperature errors, relative freedom from interfering water vapor bands, good weighting functions for column measurements across the lower troposphere, and high technology readiness of the lasers in this wavelength region. To further reduce residual temperature errors in the CO_2 measurement, a concurrent passive measurement of temperature along the satellite ground-track with an accuracy of better than 2 K is required. Atmospheric pressure/density effects on deriving the CO_2 mixing ratio columns can be addressed by a combination of simultaneous CO_2 and O_2 density column measurements to the surface/cloud tops, or possibly with surface/cloud top altimetry measurements from a lidar in conjunction with advanced meteorological analysis for determining the atmospheric pressure profile across the measured CO_2 density column. The concurrent on-board O_2 measurements are preferred and can be based on measurements using an O_2 absorption line in the 0.76 or 1.27 µm band. The mission requires a sun-synchronous, polar orbit at an altitude of about 450 km and with a lifetime of at least 3 years. The mission does not have strict requirement for specific temporal revisit or map revisit times because the data will be assimilated on each pass and the large-scale nature of the surface sources and sinks will emerge from the geographical gradients of the column integrals. The important coverage is day and night measurements covering nearly all latitudes and surfaces to separate effects of photosynthesis and respiration. Maximum power required would be about 500 W, with 100% duty cycle. Swath size would be about 200 m.

Ideally, a CO sensor should complement the lidar CO_2 measurement. The two measurements are highly synergistic and should be coordinated for time and space sampling, with the minimal requirement that the two experiments be launched close together in time to sample the same area.

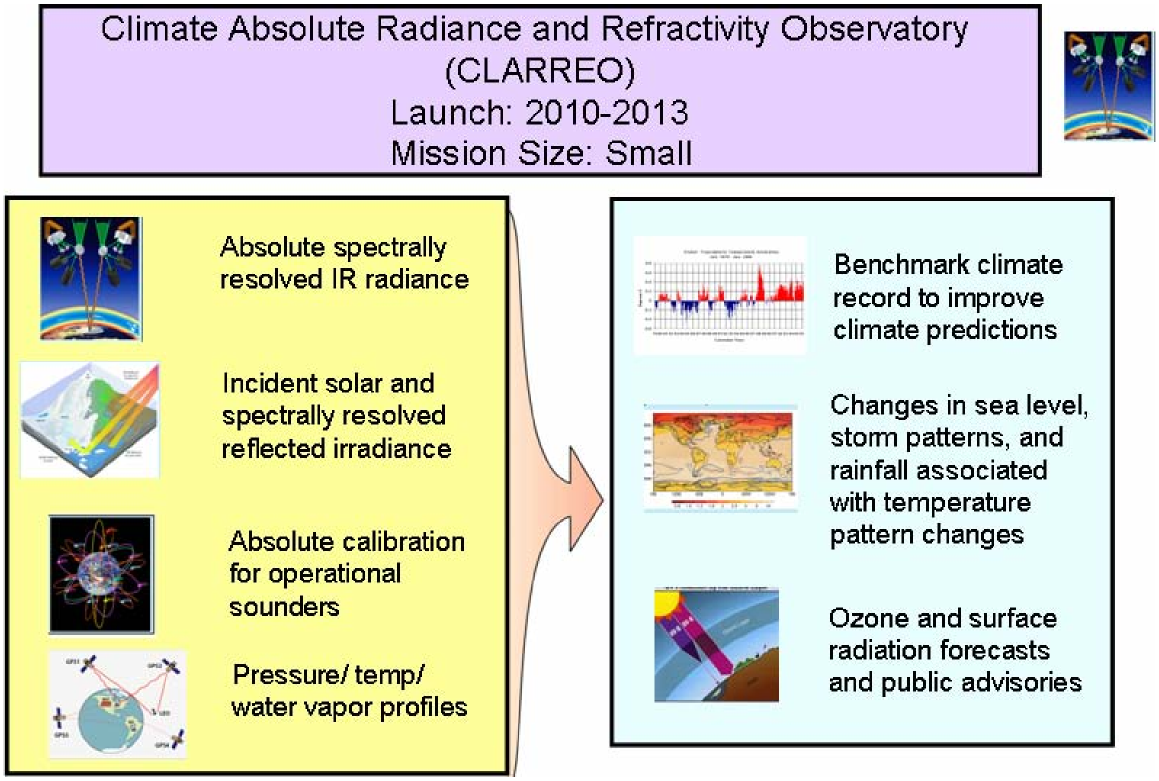
Cost: ~$400M

Schedule: ASCENDS should be launched to overlap with OCO and hence in the 2013-2016 (the mid-timeframe). Technology development must include extensive aircraft flights demonstrating not only the CO_2 measurement in a variety of surface and atmospheric conditions, but also the O_2-based pressure measurement.

Further Discussion: Land-Use, Ecosystems, and Biodiversity (Chapter 7) Section 7.5.4

Related RFI(s): 4, 20

Climate Absolute Radiance and Refractivity Observatory (CLARREO)



Climate Absolute Radiance and Refractivity Observatory
(CLARREO)
Launch: 2010-2013
Mission Size: Small

- Absolute spectrally resolved IR radiance
- Incident solar and spectrally resolved reflected irradiance
- Absolute calibration for operational sounders
- Pressure/ temp/ water vapor profiles

- Benchmark climate record to improve climate predictions
- Changes in sea level, storm patterns, and rainfall associated with temperature pattern changes
- Ozone and surface radiation forecasts and public advisories

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) will provide a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards.

Decision support for vital choices regarding water resources, human health, natural resources, energy management, ozone depletion, civilian and military communications, insurance infrastructure, fisheries, and international negotiations is necessarily linked to our understanding of climate. Effectively addressing each of these societal concerns depends upon accurate climate records and credible long-term climate forecasts. To this end, *development* of climate forecasts that are tested and trusted requires a chain of strategic decisions to establish fundamentally improved climate observations that are suitable for the direct testing and systematic improvement of long-term forecast performance. This strategy sets the foundation for the CLARREO mission.

CLARREO addresses three key societal objectives: 1) the essential responsibility to present and future generations to put in place a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards; 2) the development of an operational climate forecast that is tested and trusted through a disciplined strategy using state-of-the-art observations with mathematically-rigorous techniques to systematically improve those forecasts to establish credibility; and 3) disciplined decision structures that assimilate accurate data and forecasts into intelligible and specific products that promote international commerce as well as societal stability and security.

Background: Stripped to its fundamentals, the climate is first affected by the long-term balance between (1) the solar irradiance absorbed by the Earth, ocean, atmosphere system, and (2) the infrared (IR) radiation exchanged within that system and emitted to space. Thus, key observations include the solar irradiance, incident and reflected, and the spectrally resolved IR radiance emitted to space that carries the spectral signature of IR forcing of climate and the resulting response of that climate system. As a key part of the recognized imperative to develop long-term, high accuracy time series with global coverage of critical climate variables, this mission addresses the objective of establishing global, long-term climate records that are of *high accuracy and tied to international standards* maintained in the U.S. by the National Institute of Standards and Technology (NIST). In addition, it is essential for societal objectives that require the long-term climate record, that the accuracy of the core benchmark observations be verified against absolute standards *on-orbit* by fundamentally independent methods.

Scientific Objectives: Four elements constitute the CLARREO scientific strategy.

- First, absolute spectrally resolved radiance in the infrared measured with high accuracy (0.1 K 3σ brightness temperature) by downward-directed spectrometers in Earth orbit. Both the radiative *forcing* of the atmosphere resulting from greenhouse gas emissions and aerosols and the *response* of the atmospheric variables are clearly observable in the spectrally resolved signal of the outgoing radiance. Similarly, large differences among model projections of temperature, water vapor, and cloud distributions imply, for each model, different predicted changes in absolute, spectrally resolved radiation. The spectrum of IR radiance, if observed accurately and over the full thermal band, carries decisive diagnostic signatures in frequency, spatial distribution and time.
- Second, solar radiation, reflected from the Earth-atmosphere system back to space constitutes a powerful and highly variable forcing of the climate system through changes in snow cover, sea ice, land-use, aerosol, and cloud properties. Systematic, spatially resolved observations of the time series of absolute spectrally resolved flux of near ultraviolet, visible, and near infrared radiation returned to space by the Earth system tied to NIST standards in perpetuity underpin a credible climate record of the changing Earth system. In combination with the establishment of the absolute spectrally resolved solar irradiance reflected from the Earth-atmosphere system to Space, it is essential to continue the long-term, high accuracy time series of incident solar irradiance.
- Third, Global Navigation Satellite Systems (GNSS) radio occultation offers an ideal method for benchmarking the climate system because much of the infrastructure for this active limb sounding technique already exists, or soon will, in the form of the U. S. Global Positioning System (GPS) and the European Galileo satellites, because orbiting GNSS receivers are comparatively inexpensive, and because the technique is a measurement of frequency shift against a time standard, it is directly traceable to international standards. GNSS radio occultation profiles the refractive properties of the atmosphere by observing the timing delay of GNSS signals induced by the atmosphere as the ray descends into the atmosphere in a limb-sounding geometry. The index of refraction is directly related to pressure, temperature, and water vapor concentration in a way wherein the refractive index can be easily simulated from model output. Moreover, both GNSS and absolute, spectrally-resolved radiance in the thermal IR are accurate to 0.1 K traceable to SI standards on-orbit so that they represent completely independent, absolute records that allow, for the first time, the determination of systematic error in the climate record.
- Fourth, CLARREO will serve as a high accuracy calibration standard for use by the broadband CERES instruments on-orbit. In addition, the suite of infrared operational sounders launched on NPP and NPOESS can use the Climate Observatory to (1) establish SI traceable accuracy on-orbit, (2) establish an independent analysis of time-dependent bias in calibrated radiance, and (3) form a basis for intercomparison of all operational sounders now and in the future.

Mission and Payload: The mission requires three satellites, each of which requires a specific orbit, and each of which includes an occultation GNSS receiver. In the first category of climate benchmark radiance measurements, two of the satellites contain redundant interferometers that have a spectral resolution of 1 cm^{-1}, and encompass the thermal infrared from 200 to 2000 cm^{-1}, are in true 90° polar orbits to provide a full scan of the diurnal harmonics as well as high latitude coverage from low Earth orbit (750 km), and each of the interferometers have an internal scene selection that includes redundant blackbodies with programmable temperatures and an external scene selection that includes deep space viewing for radiance zeroing and nadir viewing with a 100 km footprint for Earth observations. Each of these satellites is gravity gradient stabilized without additional pointing, with a separation in orbital planes of 60˚. This mission requires an SI-traceable standard for absolute radiance. Each of the interferometers carry, on-orbit, phase transition cells for absolute temperature, high aspect ratio blackbodies with direct surface emissivity measurements within the blackbodies, detector linearity, polarization and stray light diagnostics, etc., such that the key climate observations are obtained globally from space with SI traceability to absolute standards on-orbit.

In the second category of benchmark radiance measurements, the third satellite carries the IR benchmark instruments deployed in the first category, but with the addition of redundant interferometers that have a spectral resolution of 15 nm, and encompasses the near UV, visible and near IR from 300 to 2000 nm. That satellite is in a true 90˚ polar, low Earth orbit with an orbital plane 60˚ from that of the first two IR satellites. This mission also requires an SI-traceable standard for absolute radiance, but in the near UV/visible/near IR, and employs continuing work at NIST that has significantly improved the accuracy (absolute) of radiance measurements in the visible and near IR through the use of detector-based technology using helium cooled bolometers in combination with the Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) approach that provides accuracies to 3 parts in 10^3 in the visible and near IR. These standards can be employed, in a series of independent observations, to directly determine lunar irradiance that in turn will provide an evolving absolute benchmark for high (absolute) accuracy small satellites in Earth orbit. The redundant interferometers in the visible have scene selection that includes 1) simultaneous forward-backward viewing angles about the nadir, 2) deep space, and 3) episodic lunar observations to pin the absolute calibration in perpetuity. Incident solar irradiance measurements have an extended history of development and require follow-on missions. Broadband CERES instruments comprising both the shortwave and longwave spectral regions will be flown on both NPP and NPOESS as follow-on missions, and the orbit selection is such that a direct intercomparison between the NPP and NPOESS instruments can be executed against the benchmark observations on CLARREO.

The CLARREO mission has 2 components. The first consists of 3 small satellites--two to obtain absolute, spectrally resolved radiance in the thermal IR and a 3rd to continue the IR absolute spectrally resolved radiance measurements, but with the addition of benchmark observations to obtain the reflected solar irradiance. Each of the small satellites would also include a GPS receiver. The second component of CLARREO is the re-flight of the incident solar irradiance and CERES broadband instruments on NPP and NPOESS.

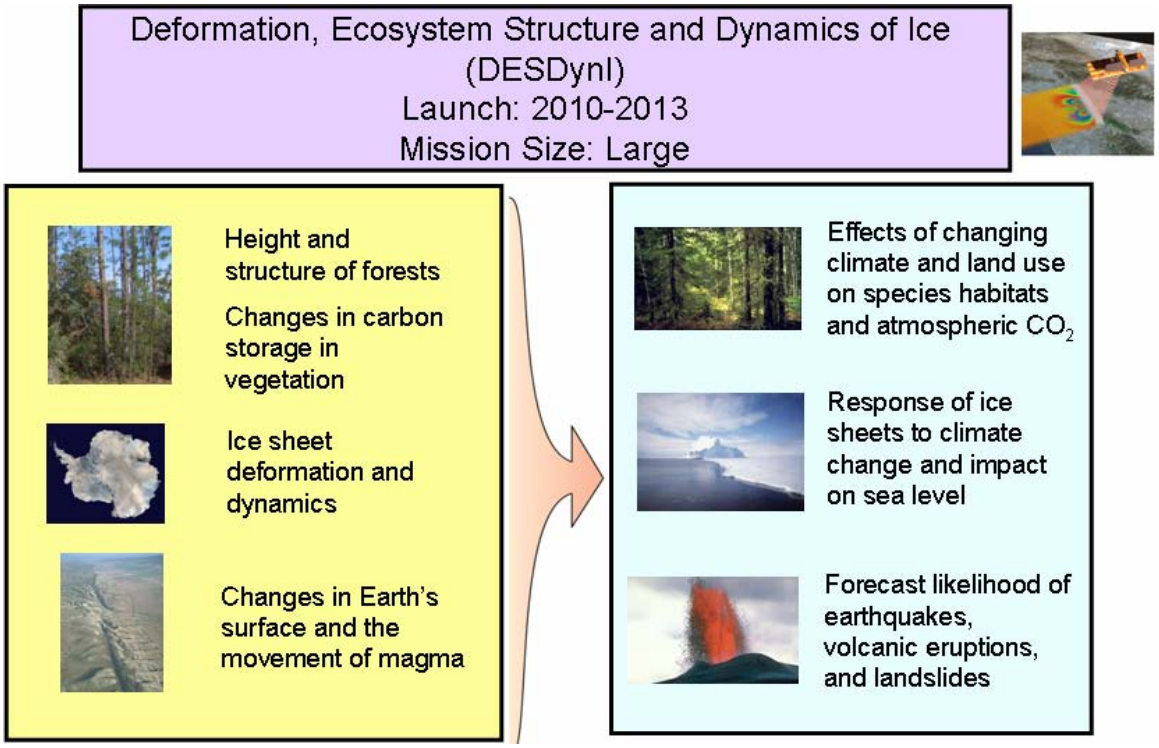
Cost: ~$65M (NOAA, for the TSIS and CERES broadband instruments) + ~$200M (NASA)

Schedule: Technology readiness for the absolute spectrally resolved IR radiance small satellite component of CLARREO is consistent with a 2008 new start, including the GPS receiver. Technology readiness for the absolute spectrally resolved visible radiance small satellite component is consistent with a 2010 new start, including the GPS receiver. Both the CERES and incident solar irradiance components of CLARREO have a complete flight heritage and are ready as the NPP and NPOESS schedules demand.

Further Discussion: Climate Change and Variability (Chapter 9) Sections 9.2.1.1.1 and 9.3.1.2.1

Related RFI(s): 16, 18

Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI)



Deformation, Ecosystem Structure and Dynamics of Ice
(DESDynI)
Launch: 2010-2013
Mission Size: Large

- Height and structure of forests
- Changes in carbon storage in vegetation
- Ice sheet deformation and dynamics
- Changes in Earth's surface and the movement of magma

- Effects of changing climate and land use on species habitats and atmospheric CO_2
- Response of ice sheets to climate change and impact on sea level
- Forecast likelihood of earthquakes, volcanic eruptions, and landslides

Surface deformation is linked directly to earthquakes, volcanic eruptions, and landslides. Observations of surface deformation are used to forecast the likelihood of earthquakes occurring as a function of location, as well as predicting both the place and time that volcanic eruptions and landslides are likely. Advances in earthquake science leading to improved time-dependent probabilities would be significantly facilitated by global observations of surface deformation, and could result in significant increases in the health and safety of the public due to decreased exposure to tectonic hazards. Monitoring surface deformation is also important for improving the safety and efficiency of extraction of hydrocarbons, for managing our ground water resources, and, in the future, providing information for managing CO_2 sequestration.

Radar and lidar measurements will help us understand responses of terrestrial biomass, which stores a large pool of carbon, to changing climate and land management. Benefits would include the potential for development of more effective land-use management, especially as climate-driven effects become more pronounced.

The poorly-understood dynamic response of the ice sheets to climate change is one of the major sources of uncertainty in forecasts of global sea level rise. DESDynI's InSAR measurements of the variations in ice flow patterns and velocities provide important constraints on their dynamic response to climate change. This knowledge will help to determine how fast society must adapt to sea level changes – knowledge crucial in planning how to allocate scarce resources.

Background: Earth's surface and vegetation cover are constantly changing on a wide range of time scales. Measuring these changes globally from satellites would enable breakthrough science with important applications to society. Fluid extraction or injection into subterranean reservoirs results in deformation of Earth's surface. Monitoring this deformation from space provides information important for managing hydrocarbons, CO_2, and water resources. Natural hazards - earthquakes, volcanoes, and landslides - on average cause thousands of fatalities and cost billions annually. These processes leave a signature surface deformation signal; measuring the deformation before and after these events leads to better risk management and understanding of the underlying processes. Climate change affects and is affected by changes in the carbon inventories of forests and other vegetation types. Changes in these land cover inventories can be measured globally. Socio-economic risks are related to the dynamics of the great polar ice sheets, which affect ocean circulation and the water cycle and drive sea level rise and fall. These processes are quantifiable globally, often uniquely, through space-based observations of changes of the surface and overlying biomass cover.

Scientific Objectives: Surface deformation data provide our primary means for recording aseismic processes, constrain interseismic strain accumulation released in large and damaging earthquakes, characterize the migration of large volumes of magma from deep in the Earth to its surface (volcanoes), and quantify the kinematics of active landslides. Earthquakes result from the accumulation of stress in the Earth; because the crust behaves as an elastic material, the strain changes observable via InSAR can be used to determine stress changes, leading to improved earthquake forecasts. Subterranean magma movement results in surface deformation. Observations of surface deformation via InSAR, particularly when combined with seismic observations, make volcanoes among the natural hazards that can be predicted most reliably. Production of hydrocarbon reservoirs results in surface deformation, typically as the result of fluid withdrawal, but also as the result of injection of fluids to stimulate production. It is often difficult to predict the trajectories of injected fluids, but observations of surface deformation can provide the needed constraints. Observations of surface deformation also will provide tools to monitor the integrity of CO_2 sequestration wells.

The horizontal and vertical structure of ecosystems is a key feature that enables quantification of carbon storage, the effects of disturbances such as fire, and species habitats. The above ground woody biomass, and its associated below ground biomass store a large pool of terrestrial carbon. Quantifying changes in the size of this pool, its horizontal distribution, and its vertical structure resulting from natural and human-induced perturbations such as deforestation and fire, as well as the recovery processes, is critical for quantifying ecosystem change.

The dynamics of ice sheets are still poorly understood because their strength is strongly dependent on their temperature, water content, conditions at their base and even their history of deformation. Direct observations of how ice sheets deform in response to changes in temperature, precipitation, etc., are crucial for achieving understanding of these important drivers of global sea level change.

Mission and Payload: This mission combines two sensors that, taken together, provide observations important for solid-Earth (surface deformation), ecosystems (terrestrial biomass structure) and climate (ice dynamics). The sensors are: 1) an L-band Interferometric Synthetic Aperture Radar (InSAR) system with multiple polarization, and 2) a multiple beam lidar operating in the infrared (~ 1064 nm) with ~ 25 m spatial resolution and 1 m vertical accuracy. The mission using InSAR to meet the science measurement objectives for surface deformation, ice sheet dynamics, and ecosystem structure has been extensively studied. It requires a satellite in 700-800 km sun-synchronous orbit in order to maximize available power from the solar arrays. An eight day revisit frequency balances temporal decorrelation with required coverage. Onboard GPS achieves cm-level orbit and baseline knowledge to improve calibration. The mission should have a 5 year life time to capture time-variable processes and achieve measurement accuracy.

For ecosystem structure, L-Band InSAR measurements allow estimating forest height with meters accuracy; polarimetry allows estimation of three-dimensional forest structure. The sensitivity of backscatter measurements at different wave polarizations to woody components and their density makes UHF radar sensors suitable for direct measurements of live above ground woody biomass (carbon stock) and structural attributes such as volume and basal area. The multi-beam laser altimeter (lidar) system would accurately measure the distance between the canopy top and bottom elevation, the vertical distribution of intercepted surfaces, and the size distribution of vegetation components within the vertical distribution. Multiple beams measure different size components of vegetation. Although this measurement is the most direct estimate of the height and the vertical structure of forests, the lidar measurement samples the Earth's surface at discrete points, rather than imaging the entire surface. DESDynI combines the two approaches, taking advantage of the precision and directness of the lidar to calibrate and validate the InSAR, especially in ecosystem types where field campaigns have not occurred. These two measurements do not need to be made simultaneously, but could be separated by up to a few weeks because ecosystem structure typically does not evolve significantly on shorter time scales. Whether both instruments are flown on the same platform or separate platforms should be determined by a more thorough study. For example, it might be possible to upgrade the ICESat-II mission to include multi-beam performance in order to meet the ecosystem requirements so long as the two missions are launched within the same time frame and take measurements within a few weeks.

The InSAR instrument consists of an L-band (1.2 GHz) radar to minimize temporal decorrelation in regions of appreciable ground cover. Two sub-bands separated by 70 MHz allow correction of ionospheric effects. The viewable swath width must be larger than 340 km to obtain complete global access. Other parameters include ground resolution better than 35 m to characterize fault geometries, noise equivalent $\sigma_{\circ}$ less than -24 dB to map radar-dark regions, electronic beam steering to minimize spacecraft interactions for acquisition and allow ScanSAR operation, and a data rate less than 140 Mbps. Multiple polarization is required for the canopy density profiles needed for ecosystem structure. As noted above, the lidar in DESDynI is a multi-beam laser ranger operating in the infrared.

Cost: ~$700M

Schedule: Technology readiness of all components is consistent with a new start now. Past studies and proposals to NASA show that all technologies required for both the InSAR and the lidar have been demonstrated in space by U.S. and/or international satellites.

Further Discussion: Solid-Earth Hazards, Resources, and Dynamics (Chapter 8) Section 8.4.1; Climate Change and Variability (Chapter 9) Section 9.3.1.3; Land-Use, Ecosystems, and Biodiversity (Chapter 7) Section 7.3.3

Related RFI(s): 44, 57, 72, 73, 83

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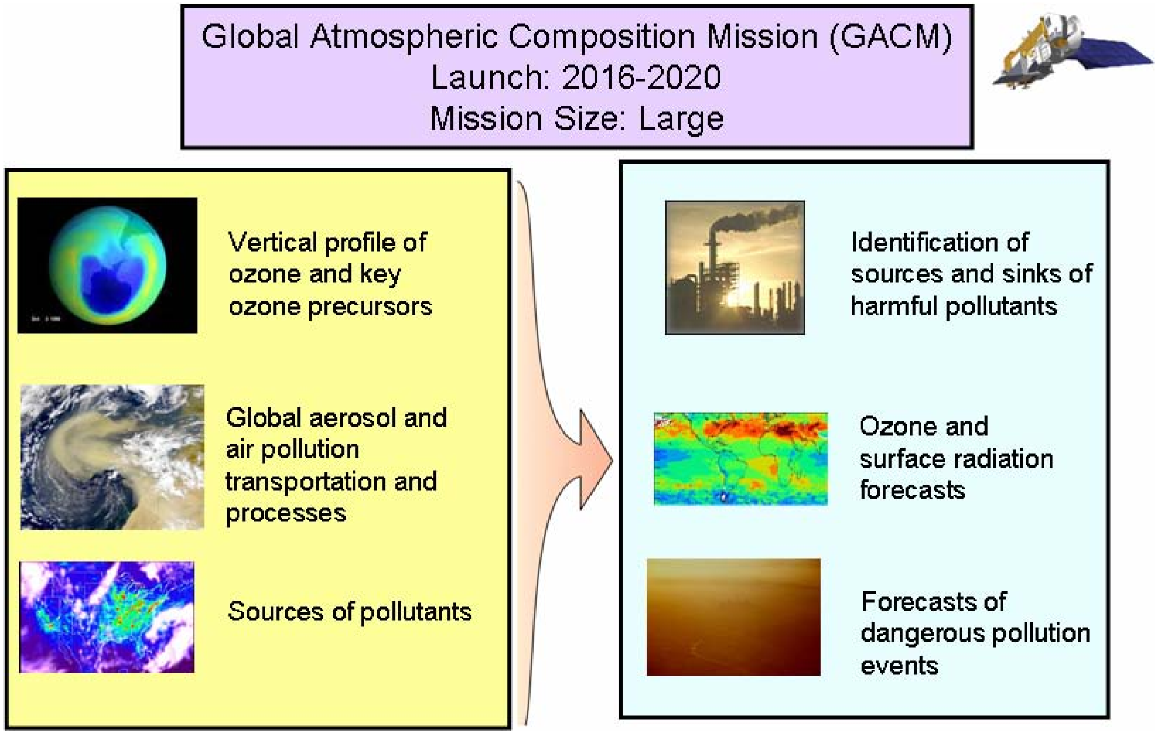
Global Atmospheric Composition Mission (GACM)



Global Atmospheric Composition Mission (GACM)
Launch: 2016-2020
Mission Size: Large

Vertical profile of ozone and key ozone precursors

Global aerosol and air pollution transportation and processes

Sources of pollutants

Identification of sources and sinks of harmful pollutants

Ozone and surface radiation forecasts

Forecasts of dangerous pollution events

Anthropogenic and natural processes are modifying the composition, chemistry, and dynamics of the global atmosphere, and there is an urgent need to observe, model, and forecast the consequence of these changes to be able to determine the best course of action to mitigate their impact. High resolution global measurements and modeling of chemistry and dynamics across the lower atmosphere directly affect chemical weather, air quality, and surface UV radiation forecasts, as well as providing global trends important to all segments of society. Potential benefits could include greater protection of public health by using predictions of air quality and surface UV radiation to help create appropriate avoidance and mitigation strategies, and by enabling the development of better public policy to avoid or reverse adverse atmospheric changes. If the latter occurs, significant ecological damage could also be averted.

Background: Anthropogenic and natural processes are modifying the composition, chemistry, and dynamics of the global atmosphere, and there is an urgent need to observe, model, and forecast the consequence of these changes to be able to determine the best course of action to mitigate their impact. Understanding and modeling the chemistry and dynamics of the lower atmosphere on regional to global scales requires a combination of measurements of O_3, O_3 precursors, and other pollutant gases and aerosols with sufficient vertical resolution to detect the presence, transport, and chemical transformation of atmospheric layers from the surface to the lower stratosphere. This is critical because of the strong vertical dependence in photochemistry and atmospheric dynamics that contribute to determining the budget of O_3 and other pollutants across the troposphere and lower stratosphere and the highly nonlinear coupling between O_3 precursors and the production of O_3. High resolution global measurements and modeling of chemistry and dynamics across the lower atmosphere directly impact chemical weather, air quality, and surface UV radiation forecasts as well as providing global trends in highly-variable processes important to all segments of society. Current satellite instruments are providing initial critical observations with low resolution across the troposphere, but a new generation of instruments and observational scenarios are required to capture the full range of needed measurements to meet the above goal. This mission was identified as a high-priority mission for both the Weather Panel to address global chemical weather objectives and the Human Health and Security Panel for air pollution and UV exposure applications.

Scientific Objectives: The specific objectives of the Global Atmosphere Composition Mission (GACM) mission are to make transformational improvement in our understanding of chemical weather processes on regional to global scales and to make a revolutionary improvement in our ability to model and forecast global atmospheric chemistry, air pollution, and surface UV radiation. Achieving these objectives requires the measurement of the global distribution of tropospheric O_3 at sufficient vertical resolution to understand tropospheric chemistry and dynamical processes in tropical, mid-latitude, and high-latitude regions and the measurement of key trace gases (CO, NO_2, CH_2O, SO_2) and aerosols that are either related to photochemical production of O_3 or that can be used as tracers of tropospheric pollution and dynamics. This mission will provide data to aid in the development and validation of chemical transport models (CTMs) under a wide range of atmospheric and pollution conditions from the tropics to the polar regions. These global measurements will also be used to connect to the more regional- and continental-scale measurements, such as from GEO, and provide more detailed vertical information than will be provided from the GEO passive instruments. This mission is complementary to the GEO air pollution mission advocated by the Weather Panel and the Human Health and Security Panel, as it provides needed observations outside of the GEO FOV that are required for up-wind boundary conditions for the continental scale GEO domain and for understanding the fate of air leaving the GEO domain. To understand the dynamics associated with stratosphere-troposphere exchange and to determine changes in the stratosphere that affect UV radiation budgets at the surface, measurements of O_3, N_2O, temperature, water vapor, and aerosols are required from the upper troposphere into the lower stratosphere.

Mission/Payload: Accomplishing the objectives of this mission requires a unique combination of passive and active remote sensing instruments in low Earth orbit (LEO). It is recommended that the passive nadir measurements of CO, O_3, NO_2, SO_2, CH_2O, and aerosols be made globally from a LEO sun-synchronous orbit. The instruments required for these measurements include an ultraviolet/visible (UV/VIS) spectrometer for daytime measurements of O_3, NO_2, SO_2, CH_2O, and aerosols and a short-wave infrared/infrared (SWIR/IR) spectrometer for daytime column measurements of CO in SWIR at 2.4 μm and day/night CO measurements in mid troposphere in IR at 4.6 μm. Special emphasis must be given to obtaining O_3 and CO column measurements with significantly enhanced sensitivity into the PBL. Limb-viewing measurements of O_3, N_2O, temperature, water vapor, CO, HNO_3, ClO, and volcanic SO_2 in the upper troposphere and lower stratosphere need to be made with an advanced microwave spectrometer.

To achieve the desired high vertical resolution O_3 measurements to better than 2 km across the mid to lower troposphere with concurrent profiles of aerosols and atmospheric structure to better than 150 m, an active system operating in a polar LEO orbit is required. These measurements can be accomplished using a differential absorption lidar (DIAL) system operating in the UV (305-320 nm) for O_3 and in the VIS (500-650 nm) for aerosols. Since the space-based O_3 DIAL requires significant technological development during the next decade, a phased implementation of this mission is recommended.

Since it is imperative that we complement the GEO air pollution mission with a global tropospheric composition mission and provide a follow-on tropospheric-stratospheric mission to extend the accomplishments of the Aura satellite instruments, we recommend that the passive portion of this mission be launched into a LEO orbit in the middle of the next decade while all the components of the more complex O_3 DIAL LEO mission are developed and tested by NASA for launch early in the following decade. It should be mentioned that NASA has already begun the initial funding of several key components of the DIAL O_3 mission as part of the Instrument Incubator Program (IIP). Since the active portion of this mission has high potential payoff for chemical weather and air pollution applications in the future, the associated technology needs to be aggressively developed during the next decade.

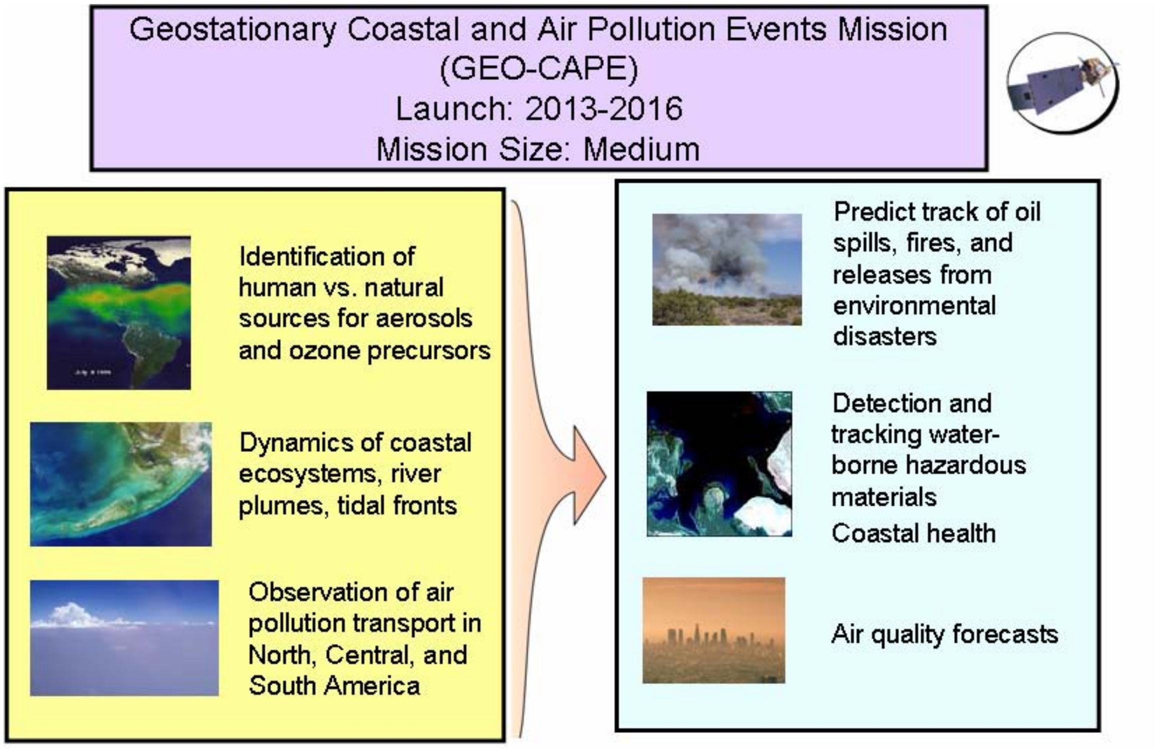
Cost: ~$600M

Schedule: Most of the sensors for the Passive LEO mission have significant heritage in existing satellite instruments (e.g., OMI, SCIAMACHY, MOPITT, GOME, MLS); however, some optimization is required for enhanced performance in the lower troposphere for O_3 and CO. The Phase-1 Passive LEO mission could be launched as early as 2017. With focused technology investment on the O_3 DIAL over the next decade, the Phase-2 LEO O_3 DIAL mission could be launched as early as 2022.

Further Discussion: Weather Science and Applications (Chapter 10) Section 10.4.3; Climate Change and Variability (Chapter 9) Sections 9.3.2.2.1-2

Related RFI(s): 3, 5, 9, 61

Geostationary Coastal and Air Pollution Events Mission (GEO-CAPE)



Geostationary Coastal and Air Pollution Events Mission
(GEO-CAPE)
Launch: 2013-2016
Mission Size: Medium

Identification of human vs. natural sources for aerosols and ozone precursors

Dynamics of coastal ecosystems, river plumes, tidal fronts

Observation of air pollution transport in North, Central, and South America

Predict track of oil spills, fires, and releases from environmental disasters

Detection and tracking water-borne hazardous materials

Coastal health

Air quality forecasts

The concentration of people living near coasts is causing enormous pressure on coastal ecosystems. These impacts are visible through declining fisheries, harmful algal blooms, and eutrophication such as the "dead zone" in the Mississippi delta, and more than 20 other persistent "dead zones" around the world. Climate change combined with continued growth of populations in coastal areas creates an imperative to monitor changes in coastal oceans. Key needs include the ability to forecast combined impacts on economically important seafood species of harvesting, coastal land management, climate change, and extreme weather events. The mission provides observations of aerosols, organic matter, phytoplankton, and other constituents of the upper coastal ocean at multiple times in the day to develop modeling capabilities for ecological and biogeochemical processes in coastal ecosystems.

The mission will also be of considerable value for improving our ability to observe and understand air quality on continental scales, and thus guide the design of air quality policy. Air pollutants (ozone, aerosols) are increasingly recognized as major causes of cardiovascular and respiratory diseases. The current observation system for air quality, based on networks of surface sites, is patently inadequate to monitor population exposure and to relate pollutant levels to their sources or transport. Continuous observation from a geostationary platform will provide the necessary data for (1) improving air quality forecasts through chemical data assimilation; (2) monitoring pollutant emissions and accidental releases, and (3) understanding pollution transport on regional to intercontinental scales.

Background: This mission advances science in two important areas, coastal ecosystems, and air quality. By having both measurements on the same platform, aerosol information derived from the air quality measurements can be used to improve the ocean ecosystem measurements.

Coastal ocean ecosystems are under enormous pressure from human activities, both from harvesting and from materials entering the coastal ocean from the land and the atmosphere. These regions contain greatly enhanced amounts of chlorophyll and dissolved organic matter compared to the open ocean, but the coastal ocean is not simply a region of enhanced primary productivity; it plays an important role in mediating the land/ocean interface and global biogeochemistry. The high productivity of the coastal ocean supports a complex food web leading to a disproportionate amount of the world's seafood harvested from the coastal ocean regions. Persistent hypoxic events or regions associated with riverine discharge of nutrients in the Gulf of Mexico, increasing frequency of harmful algal blooms in the coastal waters of the United States, and extensive closures of coastal fisheries are just a few of the issues confronting the coastal areas. Both short-term and long-term forecasts of the coastal ocean require better understanding of critical processes as well as sustained observing systems. Characterizing and understanding the short-term dynamics of coastal ecosystems is essential if we are to develop robust, predictive models of the impacts of climate change and human activity on coastal ocean ecosystem structure and function. The scales of variability in the coastal region require measurements at high temporal and spatial resolution that can only be obtained from continuous observation such as possible from geosynchronous orbit.

Air quality measurements are urgently needed to understand the complex consequences of increasing anthropogenic pollutant emissions both regionally and globally. The current observation system for air quality is inadequate to monitor population exposure and develop effective emission control strategies. Ozone and aerosol formation depend in complex and nonlinear ways on the concentrations of precursors, for which little data are available. Management decisions for air quality require emission inventories for precursors, which are often uncertain by a factor of two or more. The emissions and chemical transformations interact strongly with weather and sunlight including the rapidly-varying planetary boundary layer as well as continental-scale transport of pollution. Again, the scales of variability of these processes require continuous, high spatial and temporal resolution measurements only possible from geosynchronous orbit.

Science Objectives: The Geostationary Coastal and Air Pollution Events mission (GEO-CAPE) satisfies science objectives of both coastal ocean biophysics and atmospheric pollution chemistry. It also has important direct societal application objectives in each domain. Compatibility with objectives of the terrestrial biophysical sciences should also be explored.

Ocean objectives are: Quantify the response of marine ecosystems to short-term physical events, such as passage of storms and tidal mixing; Assess the importance of high temporal variability in coupled biological-physical coastal ecosystem models; Monitor biotic and abiotic material in transient surface features, such as river plumes and tidal fronts; Detect, track, and predict the location of hazardous materials, such as oil spills, ocean waste disposal, and harmful algal blooms; Detect floods from various sources including river overflows.

The air quality objective is to satisfy basic research and operational needs for 1) air quality assessment and forecasting to support air program management and public health, 2) emission of ozone and aerosol precursors including human versus natural sources, 3) pollutant transport into, across, and out of North, Central, and South America, and 4) large puff releases from environmental disasters. The aerosol measurements from the air quality instrument can be used to correct aerosol contamination of the high resolution coastal ocean imager.

Mission and Payload: The GEO-CAPE mission consists of three instruments in geosynchronous orbit near 80^o W longitude: 1) a UV-Vis-Near-IR wide-area imaging spectrometer (7 km nadir pixel) capable of mapping North and South America from 45 ^{o}S to 50 ^{o}N at approximately hourly intervals, 2) a steerable high-spatial resolution (250 m) event imaging spectrometer with a 300 km field of view, and 3) an IR correlation radiometer for carbon monoxide (CO), mapping over a field consistent with the wide-area spectrometer. The solar backscatter data from the UV to the near IR will provide aerosol optical depth information for assimilation into aerosol models and downscaling to surface concentrations. The same data will provide high-quality NO_2 and formaldehyde (HCHO) tropospheric columns from which emissions of NO_x and volatile organic compounds (VOCs), precursors of both ozone and aerosols, can be retrieved. Combination of the near-IR and thermal IR data will achieve vertical CO, an excellent tracer of long-range transport of pollution. The high resolution event imager would serve as a multi-disciplinary programmable scientific observatory as well as an immediate-response sensor for possible disaster mitigation. The high-resolution event imaging spectrometer will be coupled to the data generated by the wide-area spectrometer through onboard processing to target specific episodes (e.g., forest fires, pollution events, industrial accidents) that would benefit from high spatial resolution analysis. A significant fraction of its time would be made available for direct support of selected aircraft and ground-based campaigns or special observing opportunities.

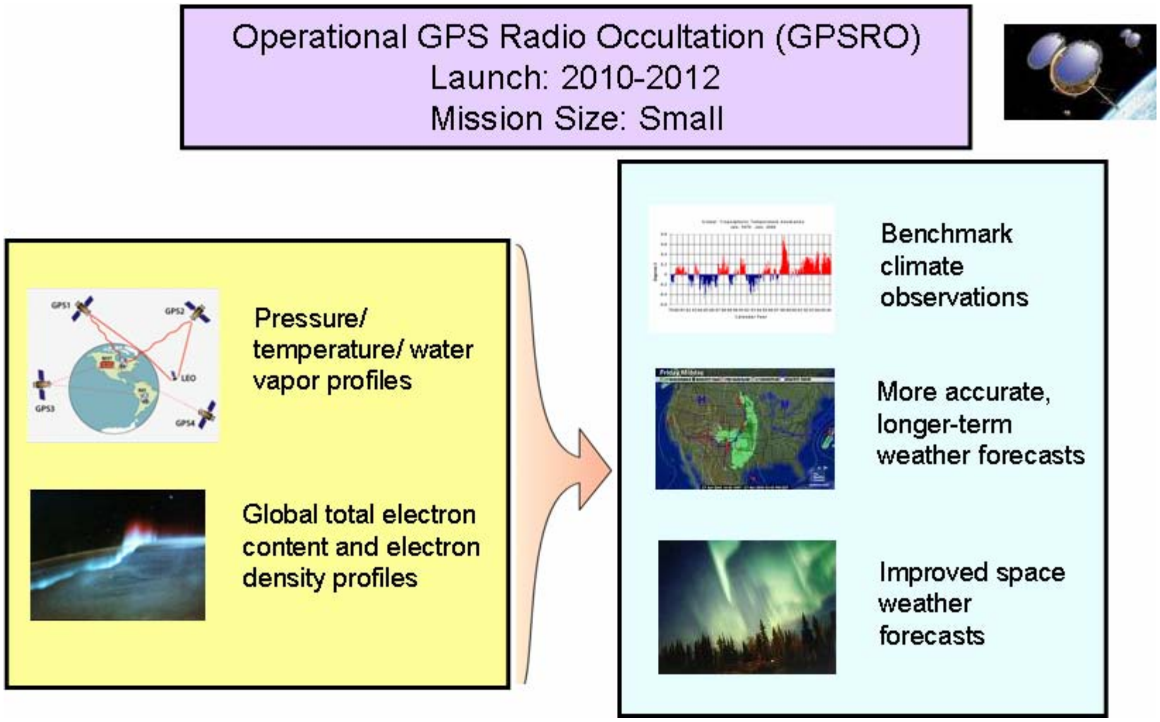
Mission Cost: ~$550M

Schedule: All of the instruments have low-earth orbit space heritage and are at high TRL. Launch would be feasible by 2015.

Further Discussion: Weather Science and Applications (Chapter 10) Sections 10.3.4; Land-Use, Ecosystems, and Biodiversity (Chapter 7) Section 7.5.5

Related RFI(s): 21, 52, 30, 60, 105

Operational GPS Radio Occultation (GPSRO)



Operational GPS Radio Occultation (GPSRO)
Launch: 2010-2012
Mission Size: Small

Pressure/ temperature/ water vapor profiles

Global total electron content and electron density profiles

Benchmark climate observations

More accurate, longer-term weather forecasts

Improved space weather forecasts

The radio occultation (RO) sounding technique produces independent information on the vertical structure of electron density in the ionosphere, temperature in the stratosphere, and temperature and water vapor in the troposphere. The ionospheric electron density profiles provide global analyses of electron density. These analyses will be useful for space weather analyses and forecasts, which in turn are important for mitigating against a number of issues that affect society in important ways such as:

- Satellite damage and difficulties: drag, degraded solar panels, lost satellites, phantom commands
- Radiation dangers to astronauts and airline passengers
- Communication blackouts and radio interference
- Flow of currents on pipelines and increased corrosion of pipes
- Electrical power problems: blackouts, power grid disruptions, transformer failures

In the stratosphere and troposphere, there are two major societal benefits: 1) monitoring climate, climate variability, and climate change with improved accuracy and precision, and 2) improving operational weather prediction. For climate, RO soundings have an accuracy, precision, and stability over time that makes them ideal benchmark climate observations. For weather prediction, RO observations improve the accuracy of temperature and water vapor analyses and contribute to increased skill of weather forecasts on time scales of hours to many days, and hence are of great immediate value to society.

Background: Radio occultation observations are becoming widely recognized for their unique and broad contributions to atmospheric and hydrologic sciences, climate and weather forecasting at an extremely low cost. The RO technique produces precise, accurate, and high vertical resolution soundings of atmospheric refractivity, which is a function of electron density in the ionosphere, temperature in the stratosphere and upper troposphere, and temperature and water vapor in the lower troposphere. Several proof-of-concept single-satellite research missions have demonstrated the powerful characteristics of RO observations, and an operational demonstration mission consisting of a constellation of six satellites called the Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC) was launched in April 2006 (www.cosmic.ucar.edu/). **Planning for a rapid transition from research into operations, we recommend that NOAA continue RO observations on an operational basis by completing the COSMIC mission through the end of its useful lifetime (2010 or 2011) and beginning a new operational mission as the COSMIC mission ends.** We define operational as meaning long-term (sustained, continuous) systematic, reliable and robust, and available in real time for a variety of applications and scientific research uses. The proposed concept involves maintaining a constellation of small satellites producing RO observations continuously to help meet the weather, climate, hydrologic, and space weather requirements as part of an integrated Earth observing system. **Additionally, GPS receivers should be placed on other LEO satellites as opportunities arise.**

Scientific Objectives: Accurate, precise, all-weather, high temporal and spatial resolution global profiles of temperature and water vapor are basic requirements of a sustained global observing system to support the understanding and prediction of virtually all aspects of weather, including such high-impact phenomena such as hurricanes and heavy precipitation events. They are also key to understanding and monitoring climate variability and change, the hydrologic cycle, and atmospheric processes such as stratospheric-tropospheric exchange. In the ionosphere, global observations of total electron content (TEC) and electron density profiles at unprecedented vertical and temporal resolution and horizontal sampling density are needed for research and operational space weather prediction. With the reduction in capabilities of NPOESS to produce vertical profiles of electron density and stratospheric and tropospheric temperatures and water vapor and threats to the GOES-R hyperspectral sounder, this mission becomes even more important to meet the scientific and operational objectives of an Earth observing system.

Mission and Payload: The proposed mission is to maintain a constellation of approximately six small satellites in low-Earth Orbit (LEO) indefinitely to support operational weather and space weather prediction and research in weather, climate and ionospheric processes. Additional GPS receivers should be placed on all other suitable LEO satellites if possible. Plans should be developed for an operational processing facility and research to effectively use RO observations should continue using COSMIC and other GPS missions.

The payload will be advanced radio occultation receivers that can receive GPS, GLONASS, and Galileo radio signals. The advanced receivers may be obtained commercially.

Cost: ~$150M[9]

Schedule: The technology has been demonstrated with the proof-of-concept GPS-MET experiment and following radio occultation missions CHAMP, SAC-C, and the early months following the COSMIC launch. Plans for an operational constellation should begin now, with launch at the end of the COSMIC mission (approximately 2012).

Further Discussion: Weather Science and Applications (Chapter 10) Sections 10.3.3 and 10.4.2; Climate Change and Variability (Chapter 9) Section 9.3.1.2

Related RFI(s): 16, 92

Supporting Documents and Recommendations: The GPS radio occultation technique is a relatively new technology, but the value of the observations has been recognized by the international community:

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[9] Average annual cost ~$25M per year. To make the cost comparable to other single missions in our recommendations, we use a figure of $150M (six years of operation)

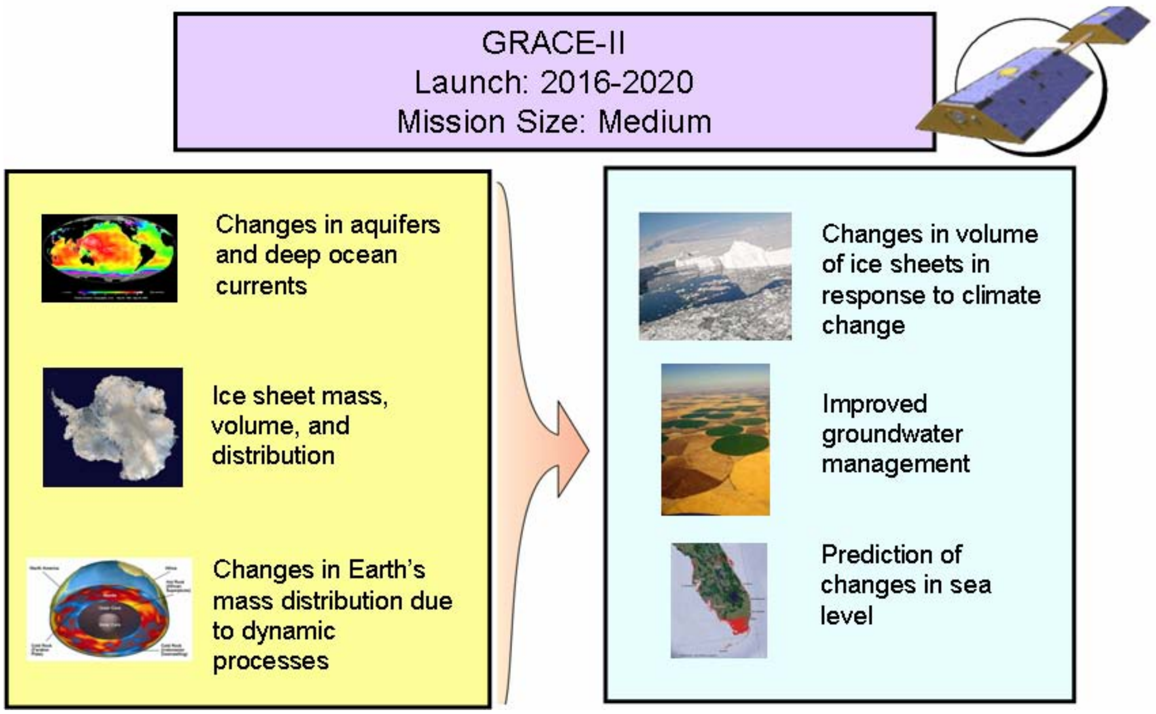
GCOS, 2003: The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC. GCOS-82 (WMO/TD No. 1143), 74 pp.

WMO, 2004: Implementation Plan for the Global Observing System for Climate in Support of the UNFCC, GCOS-92, WMO/TD 1219, 136 pp.

GCOS, 2006a: Systematic observation requirements for satellite-based products for climate-supplemental details to the GCOS Implementation Plan. GCOS-107. WMO/TD No. 1338, pp. 15-17. Recommendation A20 p. 67: *"GPS RO measurements should be made available in real time, incorporated into operational data streams, and sustained over the long-term. Protocols need to be developed for exchange and distribution of data."*

GCOS, 2006b: CEOS response to the GCOS Implementation Plan September 2006. Satellite observations of the climate system. GCOS SC-XIV Doc. 17. 56 pp. See pages 5-7. "Action A-2: CEOS will strive to ensure continuation of GPS RO measurements with, at a minimum, the spatial and temporal coverage established by COSMIC by 2011."

GRACE-II



GRACE-II
Launch: 2016-2020
Mission Size: Medium

Changes in aquifers and deep ocean currents

Ice sheet mass, volume, and distribution

Changes in Earth's mass distribution due to dynamic processes

Changes in volume of ice sheets in response to climate change

Improved groundwater management

Prediction of changes in sea level

GRACE gives a globally-consistent measurement of the Earth's mass distribution and its variability in time and space. This mass variability is primarily due to water motion. Thus, the measurement provides an integral constraint on many geophysical processes related to land, ocean, atmosphere, and glaciological subsystems. A record of time variations in the Earth's gravity field reflects the redistribution and exchange of mass within and between these reservoirs. Over one-quarter of the world's population relies on groundwater as its principal source of drinking water. Yet, global observations of this critical resource are highly variable in density, with most *in situ* observations located within heavily-exploited groundwater basins in the developed world, and few elsewhere.

GRACE-II would provide information about variations in groundwater storage at spatial resolutions sufficient to help improve resource characterization and management in those portions of the world (which include most underdeveloped countries) where groundwater is not actively managed. A more indirect benefit will be improved characterization of water storage in the subsurface, which affects weather and climate model estimates of water recycling to the atmosphere, and hence precipitation prediction at both weather and climate time scales. At present, the dynamics of water storage in surface soils vs. deeper storage as groundwater is not discriminated in land surface models, as there is little observational basis for doing so. Hence, essentially all variations in subsurface storage are attributed to soil moisture, and the lower frequency variations associated with groundwater are ignored. GRACE-II data would help foster a new generation of land surface models, which would better represent subsurface moisture variations, and, in turn, the recycling of moisture to the atmosphere.

Background: A number of dynamic processes of the Earth system result in variations in mass with time and position. In March 2002, the Gravity Recovery and Climate Experiment (GRACE) was launched to monitor these variations. GRACE consists of twin satellites separated by ~200 km along-track in a circular 450 km altitude near-polar orbit. A dual-frequency K-band ranging system provides accurate estimates of the range change between the two satellites, accelerometers provide measurements of the non-gravitational forces acting on the satellites, and dual-frequency GPS receivers provide the satellite positions. The change in the distance between the satellites is related to the gravitational signal associated with the Earth's mass distribution. By repeating the measurements at monthly intervals, the change in mass distribution can be determined. At seasonal periods, the mass change has a strong component related to water movement. The GRACE mission, which was developed with an expected 5-year lifetime, is likely to end by 2013.[10]

GRACE has demonstrated the ability to monitor variations in water mass stored on the continents, variations in global ocean mass associated with eustatic sea level change, and variations in the mass of the Greenland and Antarctic ice sheets, with a spatial resolution of 400 – 500 km. The GRACE gravity measurements over the ocean allow global measurements of pressure differences associated with surface and deep ocean currents and provide constraints on models for the general ocean circulation. The somewhat-improved spatial resolution of a proposed GRACE follow-on mission (denoted here as "GRACE-II"), and the continuation of the observation record would provide invaluable observations of the long-term climate-related changes in mass of the Antarctic and Greenland Ice Sheets, as well as the Arctic ice caps.

Scientific Objectives: Measuring temporal variations in Earth's gravity field provides fundamental constraints on our understanding of an exceptional number of interlinked components of the Earth system. These include processes affecting the hydrologic cycle and our climate, including large-scale evapo-transpiration, soil moisture inventory, and depletion of large aquifers. Changes in deep ocean currents result in dynamic pressures that cause regional sea level changes that affect the gravity field. Measuring the gravitational signal from the oceans, when combined with satellite altimetry, constrains the cause of the eustatic component of sea level rise, allowing ocean thermal expansion to be separated from an increase in mass due to the addition of freshwater from the continents. Gravity monitoring allows the determination of changes in the mass and spatial distribution of ice in Antarctica, Greenland, and continental glacier systems, as well as changes in mass associated with melting of permafrost. Gravity variations also result from the viscoelastic response of the Earth as it responds to changes in ice loads, providing important constraints on the strength of Earth's interior. Even changes in the flow in Earth's core associated with temporal variations in the geomagnetic field result in mass redistributions that lead to observable variations in the gravity field observable from space.

Mission and Payload: GRACE-II improvements include 1) more accurate measurement of inter-satellite range using either a laser satellite-to-satellite interferometer (SSI) or an improved version of the current GRACE microwave ranging system, 2) improved accommodation of the surface force effects by either improved accelerometers or by drag-free satellite operation and direct ranging to the proof-masses to reduce accelerometer errors, and 3) possibly lower altitude orbits for better sensitivity to the short wavelengths of the gravity field.

The effectiveness of the dual satellite ranging measurement has been demonstrated by the current GRACE mission. The microwave ranging system on the current GRACE satellites has been demonstrated to be a mature system with high accuracy and robust operation. Although there has been no flight demonstration, the technology readiness of the higher accuracy SSI drag-free concept has been demonstrated, under an ongoing technology development effort. In addition to the need for improved sensitivity to the short wavelength components of the gravity field, mission lifetime to maximize the measurement time series should be a concern. Mission design should improve the accuracy of both the spatial and temporal resolution.

Cost: ~$450M

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[10] See < http://www.csr.utexas.edu/grace/operations/lifetime_plots/>.

Schedule: We note that the technology readiness for the microwave version of the mission is mature; however, modest development effort for the ranging system and the satellite would be required to achieve improved performance. The laser SSI, with more accurate inter-satellite ranging capability, is at a high level of technology readiness. GRACE-II is recommended for launch in the 2016-2020 timeframe.

Further Discussion: Climate Change and Variability (Chapter 9) Section 9.3.1.1.2; Water Resources and Global Hydrological Cycle (Chapter 11) Section 11.3.4.3; Solid-Earth Hazards, Resources, and Dynamics (Chapter 8); Section 8.4.4.

Related RFI(s): 42, 96

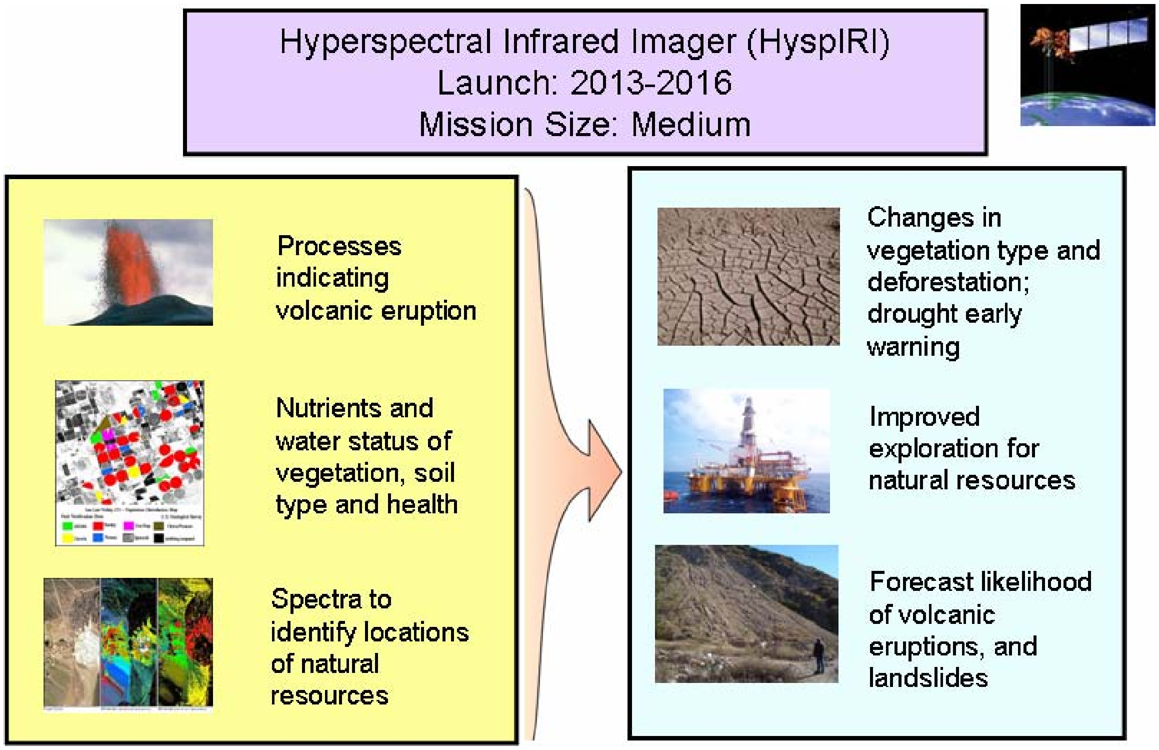
References:

National Aeronautics and Space Administration, Living on a Restless Planet, Solid Earth Science Working Group Report, Pasadena, Calif., 63 pp., 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

National Research Council, Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Envelopes, National Academy Press, Washington, D.C., 112 pp., 1997.

Committee to Review NASA's Solid-Earth Science Strategy, National Research Council, 2004. Review of NASA's Solid-Earth Science Strategy, National Academy Press, Washington, D.C.

Hyperspectral Infrared Imager (HyspIRI)



Hyperspectral Infrared Imager (HyspIRI)
Launch: 2013-2016
Mission Size: Medium

Processes indicating volcanic eruption

Nutrients and water status of vegetation, soil type and health

Spectra to identify locations of natural resources

Changes in vegetation type and deforestation; drought early warning

Improved exploration for natural resources

Forecast likelihood of volcanic eruptions, and landslides

Ecosystems respond to changes in land management and climate through altered nutrient and water status in vegetation, as well as changes in species composition. A capability to detect such changes provides possibilities for early warning of detrimental ecosystem changes such as drought, reduced agricultural yields, invasive species, reduced biodiversity, fire susceptibility, altered habitats for disease vectors, and changes in health and extent of coral reefs. Through timely, spatially-explicit information, the observing capability can provide input to decisions about management of agriculture and other ecosystems to mitigate negative impacts. The observations also underpin improved scientific understanding of ecosystem responses to climate change and management, which ultimately underpins modeling and forecasting capabilities for ecosystems. These, in turn, feed back into the understanding, prediction, and mitigation of factors driving climate change.

Volcanoes present growing hazards to large populations. The key to an ability to make sensible decisions about preparation and evacuation is the detection of the volcanic unrest that may precede eruptions, marked by noticeable changes in the visible and IR centered on craters. Assessment of soil type is an important component of predicting susceptibility to landslides. Remote sensing provides information critical for exploration for minerals and energy sources. In addition, environmental problems such as mine waste drainage and soils unsuitable for habitation, soil degradation, petroleum reservoir status, and oil pipeline leakage in remote areas can be detected and analyzed using modern hyperspectral reflective and multispectral thermal sensors.

Background: Global observations of multiple surface attributes are important for a wide range of Earth system studies. Requirements of ecosystem studies include canopy water content, vegetation stress and nutrient content, primary productivity, ecosystem type, invasive species, fire fuel load and moisture content, and disturbances such as fire and insect damage. In coastal areas, measurements of the extent and health of coral reefs are important. Observations of surface characteristics are crucial for exploration for natural resources, as well as for managing the environmental impact of their production and distribution. Forecasting of natural hazards such as volcanic eruptions and landslides is facilitated by observations of surface properties.

Scientific Objectives: The mission aims to detect responses of ecosystems to human land management and climate change and variability. For example, drought initially affects the magnitude and timing of water and carbon fluxes, causing plant water stress, mortality, and possibly wildfire and changes in species composition. Disturbances and changes in the chemical climate such as ozone and acid deposition cause changes in leaf chemistry and possibilities for invasive species. The mission can detect early signs of ecosystem changes through altered physiology, including agricultural systems. Observations also detect changes in health and extent of coral reefs, a bellwether of climate change. These capabilities have been demonstrated in space-borne imaging spectrometer observations but have not been possible globally with existing multispectral sensors.

Variations in mineralogical composition result in variations in the optical reflectance spectrum of the surface, indicating the distribution of geologic materials and also the condition and types of vegetation on the surface. Gases from within the Earth, such as CO_2 or SO_2, are sensitive indicators of impending volcanic hazards. These gases also have distinctive spectra in both the optical and near IR regions. The HyspIRI mission will map surface rock and soil composition, in many cases providing equivalent information to what can be derived from laboratory X-ray diffraction analysis. These hyperspectral images will be a valuable aid in detecting the surface expression of buried mineral and petroleum deposits. In addition, environmental disturbances accompanying both past and current resource exploitation will be mapped mineralogically to provide direction for economical remediation. Detection of surface alteration and changes in the surface temperature are important precursors to volcanic eruptions and will provide information on volcanic hazards over much of the Earth that are not yet instrumented with seismometers. In addition, variations in soil properties are linked to landslide susceptibility.

Mission and Payload: HyspIRI uses imaging spectroscopy (optical hyperspectral imaging, 400-2500 nm and multispectral infrared, 8-12 μm) of the global land and coastal surface. The mission will obtain global coverage from LEO with repeat frequency of 30 days at 45 m spatial resolution. A pointing capability is required for frequent and high resolution imaging of critical events such as volcanoes, wildfires, or droughts.

The payload consists of a hyperspectral imager together with a thermal multispectral scanner, both on the same platform, and both pointable. Given recent advances in detectors, optics and electronics, it is now feasible to acquire pushbroom images with 620 pixels cross-track and 210 spectral bands in the 400-2500 nm region. By employing 3 spectrometers with the same telescope, a 90 km swath results when the Earth's curvature is taken into account. A multispectral imager similar to ASTER is required in the thermal infrared region. For the thermal channels (5 bands in the 8-12 μm region), the requirements for volcano eruption prediction are high thermal sensitivity, on the order of 0.1 K, and a pixel size of less than 90 m. An opto-mechanical scanner, as opposed to a pushbroom scanner, would provide a wide swath of as much as 400 km at the required sensitivity and pixel size.

This mission has its heritage in the imaging spectrometer Hyperion on EO-1 launched in 2000 and in ASTER, the Japanese multispectral SWIR and thermal IR instrument flown on Terra. The hyperspectral imager is of the same design used by JPL for the Moon Mineralogy Mapper (M^3) instrument on the Indian moon-orbiting mission, Chandrayaan-1, and as such will be a proven technology.

Cost: ~$300M

Schedule: mid 2015-17. Both sensors, the hyperspectral imager and the thermal infrared multispectral scanner, have direct heritage from the M^3 and ASTER instruments respectively. The hyperspectral instrument will consist of three identical instrument modules to cover the 90 km swath and the IR instrument will be a scanner to enable the 400 km swath. The technology is currently available, making a 2015 or earlier launch feasible.

Further Discussion: Land-Use, Ecosystems, and Biodiversity (Chapter 7) Section 7.5.2; Solid-Earth Hazards, Resources, and Dynamics (Chapter 8) Section 8.4.2

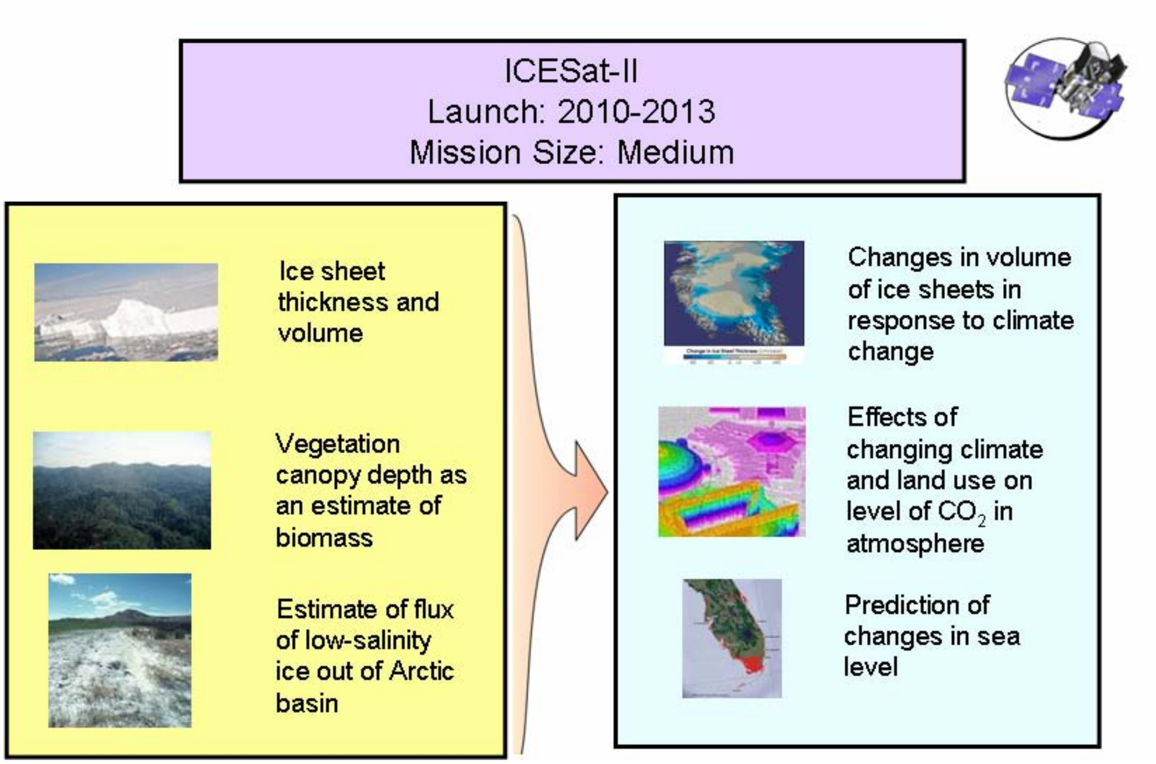
Related RFI(s): 6, 81, 89, 97

References:

National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., 63 pp., 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

Committee to Review NASA's Solid-Earth Science Strategy, National Research Council, 2004. Review of NASA's Solid-Earth Science Strategy, National Academy Press, Washington, D.C.

ICESat-II



ICESat-II
Launch: 2010-2013
Mission Size: Medium

Ice sheet thickness and volume

Vegetation canopy depth as an estimate of biomass

Estimate of flux of low-salinity ice out of Arctic basin

Changes in volume of ice sheets in response to climate change

Effects of changing climate and land use on level of CO_2 in atmosphere

Prediction of changes in sea level

Sea level rise is governed by three factors: 1) melting of permanent snow cover and mountain glaciers, 2) thermal expansion of sea level, and 3) decreases in the size of permanent ice sheets, of which changes in the size of the ice sheets is the least well constrained. The proposed measurements directly address the contribution of changing terrestrial ice cover to global sea level. As such, these measurements are key to projecting the impact of sea level change on growing populations and infrastructure along almost all coastal regions.

Canopy depth measurements using ICESat-II will address changes in terrestrial biomass, which stores a significant amount of carbon. Many factors influence the character of the vegetation, including climate, land-use, and fertilization by increased carbon dioxide. Measurement of the vegetation canopy depth will contribute significantly to our ability to assess these influences and therefore to better understand the carbon balance and future climate change.

Background: Space-borne lidar technology is a demonstrated technique for obtaining highly accurate topographic measurements of glaciers, ice sheets and sea ice. Repeated observations of the polar ice caps by NASA's ICESat system are documenting decreases in ice sheet volume. Data acquired over sea ice is proving sufficiently accurate to make the first, basin wide estimates of sea ice thickness. The technology as demonstrated so far on aircraft also can be used to measure vegetation canopy depth, which can be used as an estimator of biomass. This mission, ICESat-II, is designed as follow-on to the successful ICESat mission and will be instrumented with a highly accurate lidar instrument for repeat topographic mapping.

Scientific Objectives: Mass balance of the Earth's great ice sheets and their contributions to sea level are key issues in the area of climate variability and change. The relationships between sea level and climate have been identified as critical areas of study in the IPCC Assessments, the Climate Change Science

Program Strategy, and the U.S. IEOS. Because much of the present, past and future behavior of ice sheets are manifest in their shape, accurate observations of ice elevation changes are essential to understanding their current and likely contributions to sea level rise. ICESat-II, with high altimetric fidelity, will provide high quality topographic measurements allowing estimates of ice sheet volume change. High accuracy altimetry will also prove valuable for making long-sought repeat estimates of sea ice freeboard and hence sea ice thickness change, which is a parameter used to estimate the flux of low-salinity ice out of the Arctic basin and into the marginal seas. As yet, altimetry is the best (and perhaps only) technique for making this measurement on basin scales and with seasonal repeats. This is particularly important for climate change studies because sea ice areas and extents have been well observed from space since the 1970s and have been shown to have significant trends, but sea ice thicknesses do not have such a record. As climate change continues, ongoing, continuous measurements of both land ice and sea ice volume will be needed to observe trends, update assessments and test climate models. The altimetric measurement made with the proposed lidar, along with a higher precision gravity measurement (such as GRACE-II) would optimally measure both changes in ice sheet volume and mass, and directly contribute to understanding the ice sheet contribution to sea level rise. Coupled with the Interferometric Synthetic Aperture Radar in the DESDynI mission, the instrumentation will provide a comprehensive data set for predicting future changes of Earth's ice sheets and sea ice.

In addition to ice studies, the proposed instrument can be used to study changes in the large pool of carbon stored in terrestrial biomass. In particular, the proposed lidar can be used to measure the canopy depth and thus estimate land carbon storage so as to understand responses of biomass to changing climate and land management.

Mission and Payload: The proposed mission is to deploy an ICESat follow-on satellite to continue the assessment of polar ice changes and to complement vegetation canopy studies. The satellite will fly in low earth, non-sun-synchronous orbit.

The payload will include a single channel lidar with GPS navigation and pointing capabilities sufficient for acquiring high accuracy repeat elevation data over ice and vegetation. The proposed ICESat-II mission will address technical issues uncovered during the ICESat mission. Limitations of the lasers on ICESat are understood and will be readily corrected for ICESat-II.

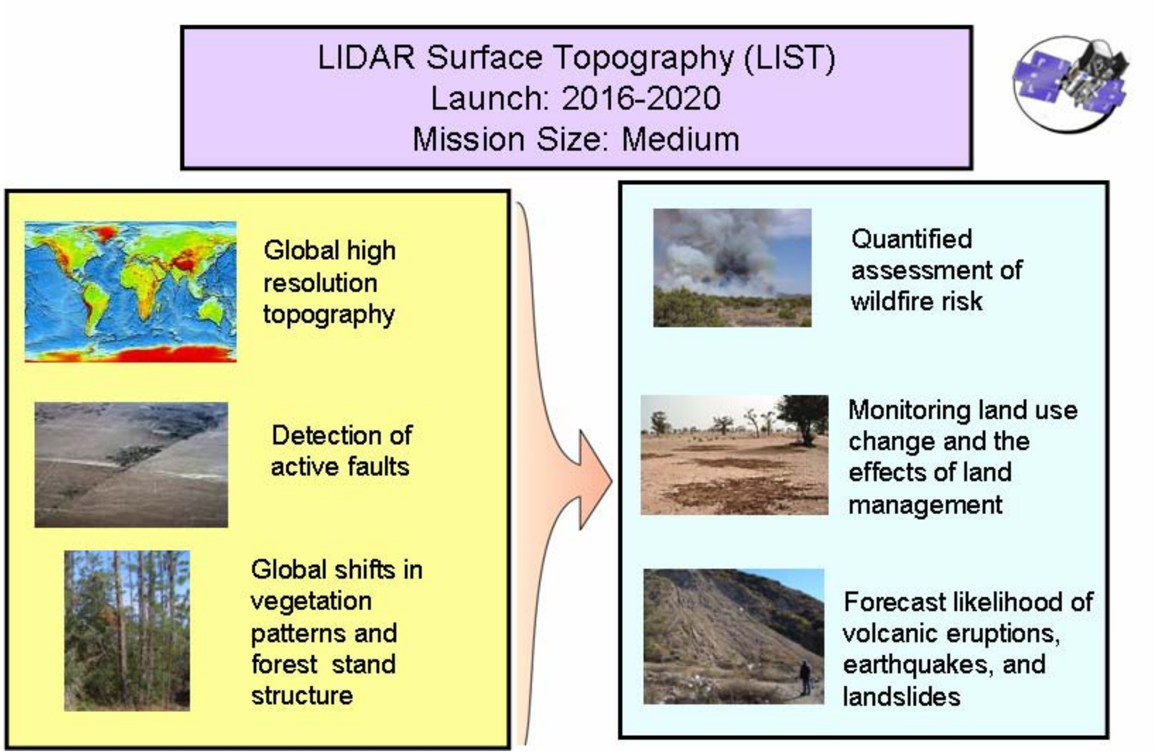
Cost: ~$300M.

Schedule: NASA has successfully demonstrated space-borne lidar technology for ice applications. This substantial heritage suggests that it is feasible to deploy a new lidar instrument by 2010 and within the timeframe of planned studies following the International Polar Year.

Further Discussion: Climate Change and Variability (Chapter 9) Section 9.3.1.1.2; Water Resources and Global Hydrological Cycle (Chapter 11) Section 11.3.4.2

Related RFI(s): 111

Lidar Surface Topography (LIST)



Predicting the location and timing of landslides, floods, tsunami runup, pyroclastic flows, and mudflows depends on precise topographic data. Global topographic data are currently available at a resolution of only 30 m to 90 m resolution, and a precision of only ~10 m in the vertical, which is simply inadequate for these purposes. The proposed 5 meter global topographic survey at decimeter precision would permit mapping of landslide and flood hazards at a small enough scale to be useful for site-specific land-use decisions. High-resolution topographic data would also advance the science on which such risk assessments are based. Precise topographic measurements would aid in finding active faults (including 'blind' faults), and thus contribute to better earthquake hazard assessments. Time series of high-precision topographic data would aid in mapping the loss of topsoil worldwide, and in detecting incipient hazards from volcanic eruptions, pyroclastic flows, and mudflows, and in determining the slip distribution in large earthquakes. The proposed lidar mapping mission would also yield global data on forest stand structure, and thus would allow quantitative assessment of wildfire risk at unprecedented scale.

Background: We live on a land surface that is dynamic in the most literal sense: Earth's surface is continually being shaped by the interplay between uplift, erosion, and deposition, as modulated by hydrological and biological processes. Surface topography alters air currents and precipitation patterns, and controls how water and soil are re-distributed across the landscape. As a result, topography regulates the spatial patterns of soil depth, soil moisture, and vegetation. It likewise influences how the risks from natural hazards -- such as landslides, floods, and earthquakes -- are distributed across the landscape. High-resolution topographic data can be analyzed to understand the tectonic forces shaping the Earth's surface, and the geologic structures through which those forces are expressed. Time series of high-precision topography can be used to observe the reshaping of Earth's surface by landslides, flooding, erosion, large earthquakes, and tsunamis. Until recently, the coarse resolution of topographic mapping has been a major impediment to understanding the forces and dynamic processes that shape the Earth's surface.

Currently, small areas can be surveyed at high resolution using airborne lidar (LIght Detection And Ranging), but airborne surveys of large areas are impractical. Space-based global coverage at 5 meter resolution would facilitate comprehensive studies of Earth's surface across diverse tectonic, climatic, and biotic settings, even in areas that are otherwise inaccessible for geographic, economic, or political reasons. Lidar also measures the height of vegetation, enabling global studies of forest stand structure and land cover dynamics. Periodic repeat surveys (on timescales of months to years) would permit large-scale measurements of erosion and deposition fluxes. More frequent repeat surveys could be targeted in locations where topography is changing rapidly (e.g., due to storms, volcanic eruptions, or earthquakes), or where topographic time series would be particularly helpful in detecting incipient natural hazards.

Scientific Objectives: High-resolution topographic data, and high-precision measurements of topographic change, are needed to: a) understand the coupling between climate, tectonics, erosion, and topography; b) estimate the geomorphic transport laws that shape the Earth's surface; c) calibrate and test models of landform evolution; d) predict -- and detect -- erosional response to climate change; e) quantify global shifts in vegetation patterns and forest stand structure in response to climate shifts and human land-use; f) infer changes in groundwater aquifers; g) measure the changes in volumes of glaciers and ice sheets; h) quantitatively map topsoil losses; and i) assess the risk of landslides, floods, tsunami runup, volcanic eruptions, and earthquakes. At present, global coverage is at a horizontal resolution of, at best, 30 m, with a vertical precision of 10 m. While useful, the threshold for major advances is at about 5 m horizontal resolution and 10 cm vertical precision.

Mission and Payload: While earlier-generation space-borne laser systems (*e.g.,* the Shuttle Laser Altimeters, ICESat) were generally single-beam systems that collected profiles of the surface along the spacecraft ground track, emerging technology will enable spatial elevation mapping. Three approaches could enable spatial mapping of Earth’s surface from an orbital platform. The first uses a single laser beam and a scanning mechanism with kilohertz-ranging rates to spatially map the surface, as demonstrated by the GSFC airborne Laser Vegetation Imaging Sensor (LVIS). The second approach takes a single laser and splits the beam in numerous parts via a diffractive optical element; separate detectors are used to measure elevation in each backscattered beam. This approach is being implemented in the design of the Lunar Obiter Laser Altimeter, to be flown on the Lunar Reconnaissance Orbiter to be launched in 2008. The third approach uses a single laser beam to illuminate a broad swatch of surface and a pixilated detector in which each pixel makes a time of flight measurement. An example that uses this approach is the Lincoln Laboratory JIGSAW airborne system; analysis has shown that 5 m mapping of the Moon could be achieved in two years using an adaptation of this system. Study will be required to determine the optimal technological approach for the high-resolution topographic mapping mission. In any case, megabit to gigabit data rates will need to be managed during mapping operations.

Cloud cover will limit the coverage available from each individual pass, so multiple passes will be required for complete coverage. A relatively long mission lifetime may be needed to achieve the desired spatial density and coverage, and repeated measurements over several years would facilitate detecting surface changes such as topsoil losses to erosion.

The mission will obtain global coverage from LEO. Global repeat coverage will be achieved on timescales of months to years, with more frequent repeat coverage of focused areas of special interest

Cost: ~$300M

Schedule: late, 2017-19

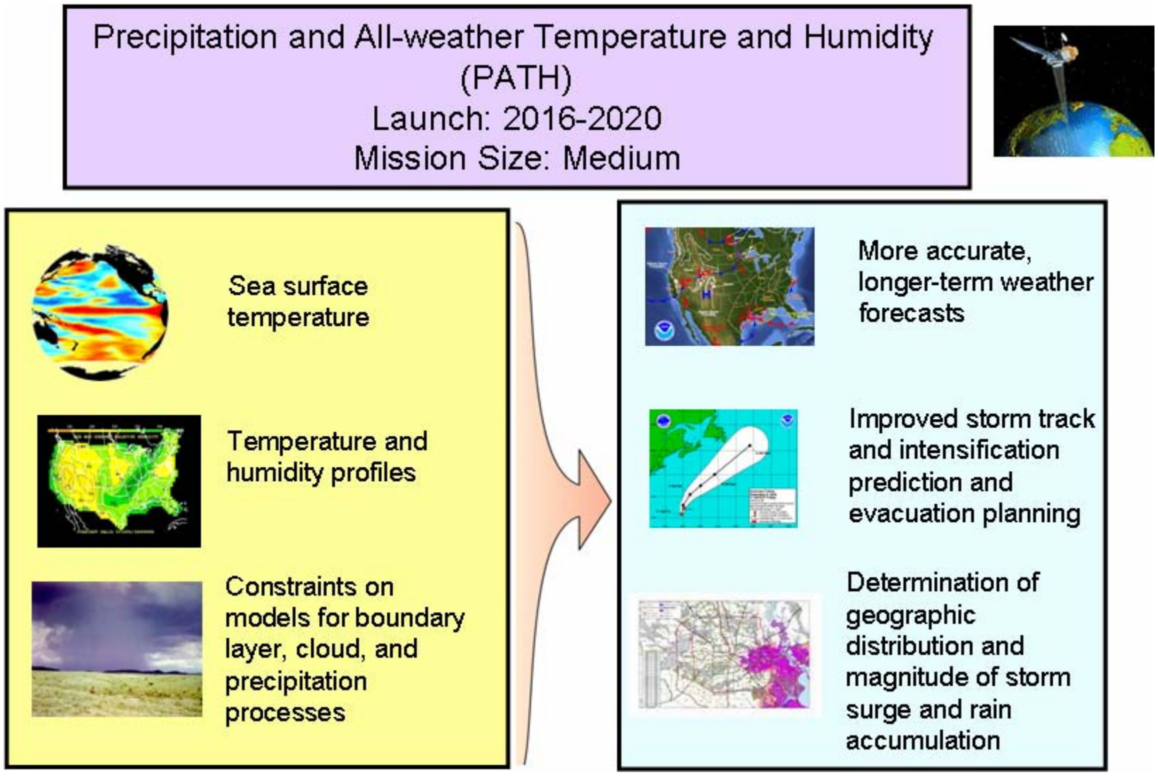
Further Discussion: Solid-Earth Hazards, Resources, and Dynamics (Chapter 8) Section 8.4.3; Climate Change and Variability (Chapter 9) Section 9.3.1.1.2; Water Resources and Global Hydrological Cycle (Chapter 11) Section 11.3.4.2

Related RFI(s): 57, 111

Supporting Documents:

National Aeronautics and Space Administration, Living on a Restless Planet, Solid Earth Science Working Group Report, Pasadena, Calif., 63 pp., 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.
Committee to Review NASA's Solid-Earth Science Strategy, National Research Council, 2004. Review of NASA's Solid-Earth Science Strategy, National Academy Press, Washington, D.C.
Committee on the Science of Earthquakes, National Research Council, 2003. Living on an Active Planet Perspectives on Earthquake Science, National Academy Press, Washington, D.C.

Precipitation and All-weather Temperature and Humidity (PATH)



Precipitation and All-weather Temperature and Humidity (PATH)
Launch: 2016-2020
Mission Size: Medium

Sea surface temperature

Temperature and humidity profiles

Constraints on models for boundary layer, cloud, and precipitation processes

More accurate, longer-term weather forecasts

Improved storm track and intensification prediction and evacuation planning

Determination of geographic distribution and magnitude of storm surge and rain accumulation

The need for early identification and reliable forecasting of the track and intensity of tropical cyclones, and of the geographical distribution and magnitude of storm surge and rain accumulation totals during and after landfall is underscored by the unprecedented extent of the 2005 hurricane season in the U.S. This is a striking example of where more accurate, more reliable and longer term forecasts, driven by fundamentally improved observations from space, could have had a direct impact on evacuation planning and execution, efficient distribution of emergency response resources, and, ultimately, the reduction in loss of life and human suffering that occurred. One critical class of observations that would enable transformational improvements in forecast skill is of the three dimensional atmospheric temperature and water vapor analyses, as well as SST and precipitation fields **under all-weather (both clear and cloudy) conditions, with temporal refreshing every 15 to 30 minutes.** This mission will do just that.

Background: Operational NOAA and DoD LEO satellites have for many years carried microwave spectrometers for atmospheric sounding of temperature, water vapor, and cloud liquid water. These LEO platforms also carry infrared sounders and the performance of each is substantially enhanced by the presence of the other, especially in cloudy conditions. IR sounders are also carried on operational NOAA platforms in GEO, but to date no microwave sounder has flown in GEO due to the limitations of available technology. The value to numerical weather prediction models of the current GEO soundings, based solely on IR observations, is significantly hampered in regions of clouds and precipitation. Recent developments in microwave imaging technology have been specifically focused on this problem. As a result, GEO microwave sounders are now a viable possibility.

Scientific Objectives: Current numerical weather prediction models are widely recognized as having an inadequate representation of the processes of cloud formation, evolution and precipitation. The models rely on simplistic parameterization schemes and an incomplete understanding of the underlying cloud microphysics to represent the most rapidly-changing weather features. Time-continuous all-weather observations will have a transformational impact on this problem in two regards. The measurements will impose powerful new constraints on, and lead to greatly improved models for boundary layer, cloud, and precipitation processes. The availability of continuous observations will also significantly mitigate the requirements on those models because they will be able to be re-initialized so frequently by observations. The observations will also enable major scientific advances in understanding of El Niño, monsoons, and the flow of tropical moisture to the U.S. Furthermore, the ocean, which covers 70% of the earth, is the lower boundary for much of the atmosphere. Sea surface temperature controls the latent and sensible heat flux and moisture flux from the ocean to the atmosphere, on which the strength and track of hurricanes and the cyclogenesis in tropical oceans depends. [11]

Mission and Payload: Temporal resolution from LEO cannot begin to approach 15-30 min without an impractically large constellation of platforms. Only a MEO or GEO mission can reasonably deliver the required time resolution. Accommodation of an all-weather sensor suite on future GOES GEO platforms is the most promising option in the next ten years. MEO platforms are a second viable option. However, while the lower MEO orbit altitude would improve spatial resolution relative to GEO, there is very little flight heritage for scientific instruments in MEO. As a result, the time scale of technology developments required for a MEO mission would be considerably longer.

All-weather retrievals of air temperature and absolute humidity profiles require spectrometric observations of microwave emission along rotational transition lines of oxygen and water vapor. The lower energy transitions, in particular in the 50-70 and 118 GHz oxygen complex and the single 183 GHz line for water vapor, are best suited for penetration into clouds. The retrieval of surface rain rate has been demonstrated using passive microwave observations by SSMI and AMSU. This method requires the same microwave spectrometer observations as do the temperature and humidity profiles. The radiometer receiver and spectrometer technologies required for tropospheric sounding are quite mature and are considered low risk.

Cost: ~$450M

Schedule: Technology readiness of critical microwave antenna, receiver, and backend electronics for a GEO mission is consistent with a ~2010-2015 new start. For integration on a GOES platform, schedule must also comply with future NOAA/GOES opportunities. Technology readiness is less advanced for a MEO mission, owing to a lack of heritage design references. Target a ~2020 new start for MEO.

Further Discussion: Weather Science and Applications (Chapter 10) Section 10.3.2

Related RFI(s): 48

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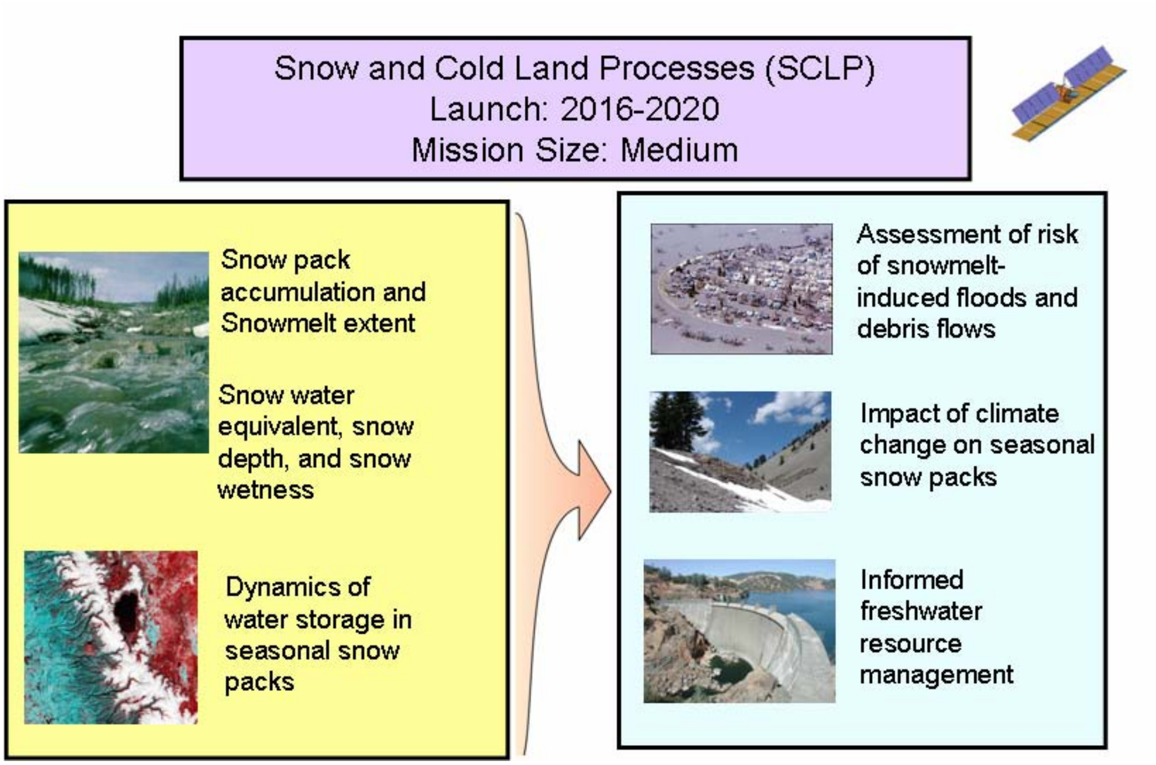
[11] PATH provides cloud-independent high temporal resolution SST to complement, not replace, global operational SST measurement

Snow and Cold Land Processes (SCLP)



Snow and Cold Land Processes (SCLP)
Launch: 2016-2020
Mission Size: Medium

Snow pack accumulation and Snowmelt extent

Snow water equivalent, snow depth, and snow wetness

Dynamics of water storage in seasonal snow packs

Assessment of risk of snowmelt-induced floods and debris flows

Impact of climate change on seasonal snow packs

Informed freshwater resource management

One sixth of the world's population, and over one-quarter of the global gross domestic product, is reliant on water supplies derived in part from seasonal snowpacks and glaciers. Fresh water derived from snow is often the principal source of potable water, and is a major source of water for irrigation, energy production, transportation, and recreation. In the western U.S., over 70 percent of streamflow is derived from winter snowmelt. Hence, understanding the dynamics of water storage in seasonal snowpacks is critical to the effective management of water resources both within the U.S. and globally. Furthermore, snow properties influence surface water and energy fluxes and other processes important to weather and climate over much of the globe, in addition to biogeochemical fluxes, ecosystem dynamics, and even certain solid-Earth hazards and dynamics. Better understanding these interactions in snow-dominated regions is important for a number of scientific and practical reasons, including prediction of the effects of high latitude lakes and wetlands on the global carbon cycle, and management of freshwater resources. Climate change seriously threatens the abundance of snow globally, and is changing the dynamics of snow accumulation and melt (in the western U.S., peak spring snowmelt runoff has advanced several weeks over the last half century). These interactions of changing climate with snow accumulation and melt dynamics will require better observations of snowpack extent and water storage. Snow can also be a significant hazard. Eight of the most damaging U.S. floods in the past century were associated with snowmelt, including the devastating Grand Forks flood of 1997 which caused over $4B in damage. SCLP will provide critical information for water resources management, as well as natural hazard mitigation.

Background: Seasonal snowpacks are a dynamic fresh water reservoir that stores precipitation and delays runoff, and in so doing plays a major role in the terrestrial water cycle of much of the Earth's land surface. One sixth of the world's population depends on snow-covered glaciers and seasonal snow for water supplies, which may be at risk from a warming climate. Fresh water derived from snow is often the principal source of fresh water for drinking, food production, energy production, transportation, and recreation, especially in mountain regions and the surrounding lowlands. Snow covers up to 50 million km^2 of the global land area seasonally (34% of total land area), affecting atmospheric circulation and climate from local to regional and global scales. Snow properties influence surface water and energy fluxes and other processes important to weather and climate, biogeochemical fluxes, ecosystem dynamics, and even certain solid-Earth hazards and dynamics. The Snow and Cold Land Processes (SCLP) mission will fill a critical gap in the current global water cycle observing system by measuring snow water equivalent (SWE), snow depth, and snow wetness over land and ice sheets.

Scientific Objectives: Scientists and managers need to know the spatial extent of snowcover and perhaps more importantly, how much water is in the snowpack and how fast is it melting. Globally, the dynamics of snowpacks can vary greatly, and by one classification scheme there are in fact seven characteristics snow domains, ranging from maritime (such as the mountains of the northwestern U.S.) to cold high latitude tundra areas. The hydrologic characteristics of snow differ for each of these snow types depending on extent of the snowcover and its water content. The extensive shallow snowpacks found in high latitude regions require high accuracy (2 cm RMSE) whereas for deep snowpacks such as in mountainous areas the requirement is less stringent (10% RMSE). Topography controls the distribution and dynamics of snowcover, which dictates spatial resolution on the order of hillslope processes – typically a few hundred m at most. In the temporal domain, intra-seasonal and synoptic-scale snow accumulation and ablation processes need to be resolved. At the intra-seasonal time scale, observations are required on the order of 15 days. To resolve the effects of individual weather events, a shorter repeat interval of 3-6 days is needed.

Mission and Payload: A mission consisting of a dual mode high frequency (X-, Ku-band, with VV- and VH-polarization) SAR and high frequency (K-, Ka-band with H-polarization) passive microwave radiometry in low earth orbit (LEO) would meet the science objectives. Microwave sensors are best suited for the measurement objectives. A combination of active and passive microwave instruments will provide the needed spatial resolution and heritage for key climate data records, respectively. The two high frequency SAR channels are sensitive to volumetric scattering in snow, but sample a range of depths and so are capable of characterizing both deep and shallow snowpacks. The X-band SAR would also be used to create a reference image thereby accounting for substrate emissivity. The dual polarization mode SAR enables discrimination of the radar backscatter into volume and surface components. The dual frequency passive microwave radiometer would provide additional information to aid the radar retrievals and would also provide a link to snow measurements from previous, recent and planned passive microwave sensors. A multi-resolution configuration would provide spatial resolution on the order of 50-100 m for spatial variability at the hillslope scale. However, it is not essential to have this resolution everywhere all of the time. Sub-kilometer spatial resolution would often be sufficient as long as 50-100 m observations were regularly available to link to finer-resolution local and hillslope-scale processes. Dual temporal resolution is also proposed with 15-day temporal resolution to capture intra-seasonal variability and a shorter repeat interval of 3-6 days to resolve the effects of synoptic weather events.

Cost: ~$500M

Schedule: The SCLP concept has heritage from QuickSCAT, SRTM, and SSM/I. A similar mission, the Cold Regions H2O (CoReH2O) mission is currently under consideration by ESA and is in the risk reduction phase. An assessment of measurement parameters and technology has been conducted by the NASA Earth Science and Technology Office. Given thet uncertainty regarding the replacement for the CMIS instrument on the NPOESS platform, the passive microwave component in this mission concept could provide some interim capability. Launch in the range of 2016-2020 is suggested, however given the proposed mission's heritage, need, and international momentum earlier launch is feasible.

Further Discussion: Water Resources and Global Hydrological Cycle (Chapter 11) Section 11.3.3

Related RFI(s): 19

Supporting Documents:

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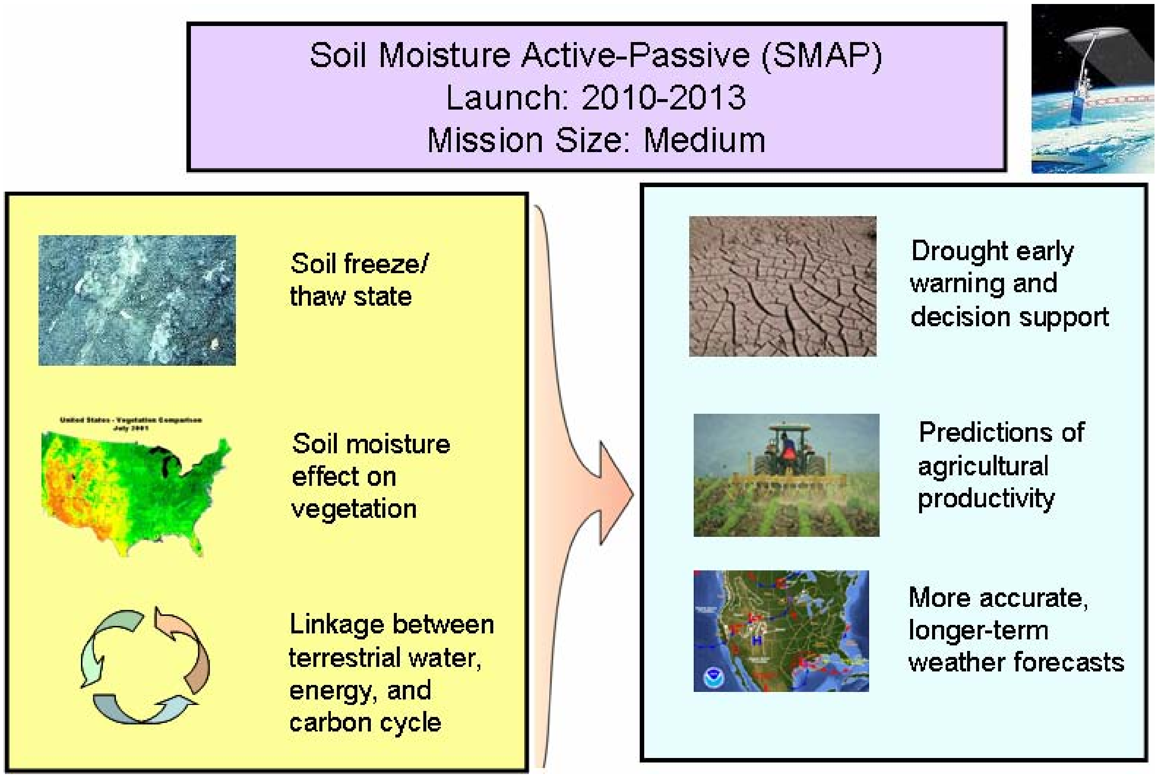
Shi, J., and J. Dozier, Estimation of snow water equivalence using SIR-C/X-SAR, Part 1: Inferring snow density and subsurface properties, IEEE Trans. Geosci. Remote Sens., 38(6), 2465-2474, 2000.

Soil Moisture Active-Passive (SMAP)



Soil Moisture Active-Passive (SMAP)
Launch: 2010-2013
Mission Size: Medium

Soil freeze/ thaw state

Soil moisture effect on vegetation

Linkage between terrestrial water, energy, and carbon cycle

Drought early warning and decision support

Predictions of agricultural productivity

More accurate, longer-term weather forecasts

Soil moisture is a key control on evaporation and transpiration at the land-atmosphere boundary. Since large amounts of energy are required to vaporize water, soil control on evaporation and transpiration also has a significant impact on the surface energy fluxes. Hence soil moisture variations affect the evolution of weather and climate over continental regions. Initialization of numerical weather prediction (NWP) models and seasonal climate models with correct soil moisture information enhances their prediction skill and extends their skillful lead-times. Soil moisture strongly affects plant growth, and hence agricultural productivity – especially during conditions of water shortage, the most severe of which is drought. At present, there is no global *in situ* network for soil moisture, and global estimates of soil moisture, and, in turn, plant water stress, must be derived from models. These model predictions (and hence drought monitoring) could be greatly enhanced through assimilation of soil moisture observations. Soil moisture and its freeze/thaw state are also key determinants of the global carbon cycle. Carbon uptake and release in boreal landscapes is one of the major source of uncertainty in assessing the carbon budget of the Earth system (the so-called "missing carbon sink"). Soil moisture also is a key variable in water-related natural hazards, such as floods and landslides. High-resolution observations of soil moisture would help to improve flood forecasts, especially for intermediate to large watersheds where most flood damages occur, and thus improve the capability to protect downstream resources. Soil moisture in mountainous areas is one of the most important determinants of landslides, hazards of which could be better predicted through consistent observations, which are presently lacking.

Background: Global mapping of soil moisture and its freeze/thaw state at high resolution is a long-standing science measurement because these variables are what fundamentally link the terrestrial water, energy and carbon cycle sciences. The measurements also have major applications in predicting natural hazards such as severe rainfall, floods, and droughts. The spatial variations of soil moisture fields are determined by precipitation and radiation forcing, vegetation distribution, soil texture heterogeneity, and topographic redistribution processes. These spatial variations lead to the need for high-resolution soil moisture mapping.[1] Numerous airborne and tower-based field experiments have shown that low-frequency L-band microwave measurements are reliable indicators of soil moisture changes across the landscape. Only with combining high-resolution active radar and high-accuracy passive radiometer L-band measurements can we produce the data products that meet the science and application requirements. The proposed SMAP soil moisture mission builds on the risk-reduction performed for the AO-3 ESSP called The Hydrosphere State (Hydros) mission.[2] The SMAP radar makes overlapping measurements, which can be processed to yield resolution-enhancement and 1-3 km resolution mapped data. The SMAP radar and radiometer share a large deployable light-weight mesh reflector that is spun to make conical scans across a wide (1000 km) swath. This measurement approach allows global mapping at 3 to 10 km resolution with 2-3 day revisit.

Scientific Objectives: Soil moisture and its freeze/thaw state are primary controls on the exchange fluxes of water, energy and carbon at the land-atmosphere interface. More importantly these variables are what link the water, energy and carbon cycles over land. The availability of soil moisture data will serve to remove existing stove-piping in the water, energy, and biogeochemistry communities by directly characterizing the link between these cycles over land regions. The data will also enable the Earth system science community to address the question of how perturbations in one cycle (radiative forcing) affect the rates of the other cycles. The spatial variability that is due to the influences of precipitation intermittency, patchy cloudiness, soil and vegetation heterogeneity and topographic factors lead to the requirement for high-resolution mapping of soil moisture and its freeze/thaw state. Currently there are no *in situ* networks to support the data needs of Earth system scientists. Forthcoming satellite missions do not have the active and passive sensor combination needed to meet the resolution requirements need to characterize the heterogeneous fields.

Soil moisture serves as the memory at the land surface in the same way as sea surface temperature does at the ocean surface. The use of sea surface temperature observations to initialize and constrain coupled ocean-atmosphere models led to significant advances in long-range weather and seasonal prediction. In the same way, high-resolution soil moisture mapping will have transformative effects on Earth system science as well as applications.[3] As the ocean and atmosphere community synergies have led to significant advances in Earth system understanding and significantly improved prediction services, the availability of high-resolution mapping of surface soil moisture will be the link between the hydrology and atmospheric communities that share the land interface. There availability of the observations will enable the emergence of a new generation of hydrologic models for applications in Earth system understanding and operational severe weather and flood forecasting.

Mission and Payload: The SMAP mission is based on one flight system in low-Earth sun synchronous orbit. SMAP includes both active radar and passive radiometer measurements. The two sensors share a single feedhorn and mesh reflector to form a beam offset from nadir with the surface of 39 degrees. This beam is rotated conically about the nadir axis to form a wide swath measurement. The reflector is composed of lightweight mesh material that can be stowed for launch. The shared feed and reflector components between the two sensors lead to significant cost-savings. The SMAP mission hardware is derived from the Hydros design and it has therefore been subject to significant amounts of study and risk-reduction. Similarly the spacecraft dynamics, ground data system and science algorithms have been tested to significant extent. Field experiments have been used to validate the science algorithms and scale models have been constructed to test the antenna performance. As a result of the Hydros risk-reduction investments and activities, the proposed SMAP mission components are all at Technology Readiness Level 7 and higher.

Cost: ~$300M.

Schedule: As a pathfinder the SMAP concept is built on the foundations of the earlier AO-3 concept (Hydros) that has been through risk-reduction phase marked by rigorous reviews. As a result, the SMAP mission is ready for "*fast-track*" towards launch as early as 2012, when there are few scheduled Earth missions. The readiness of the SMAP mission also enables gap-filling observations to meet key NPOESS community needs (soil moisture is "Key Parameter," see 4.1.6.1.6 in IORD-II Document).[4] Additionally it will serve as continuity measurements for the Aquarius mission community.

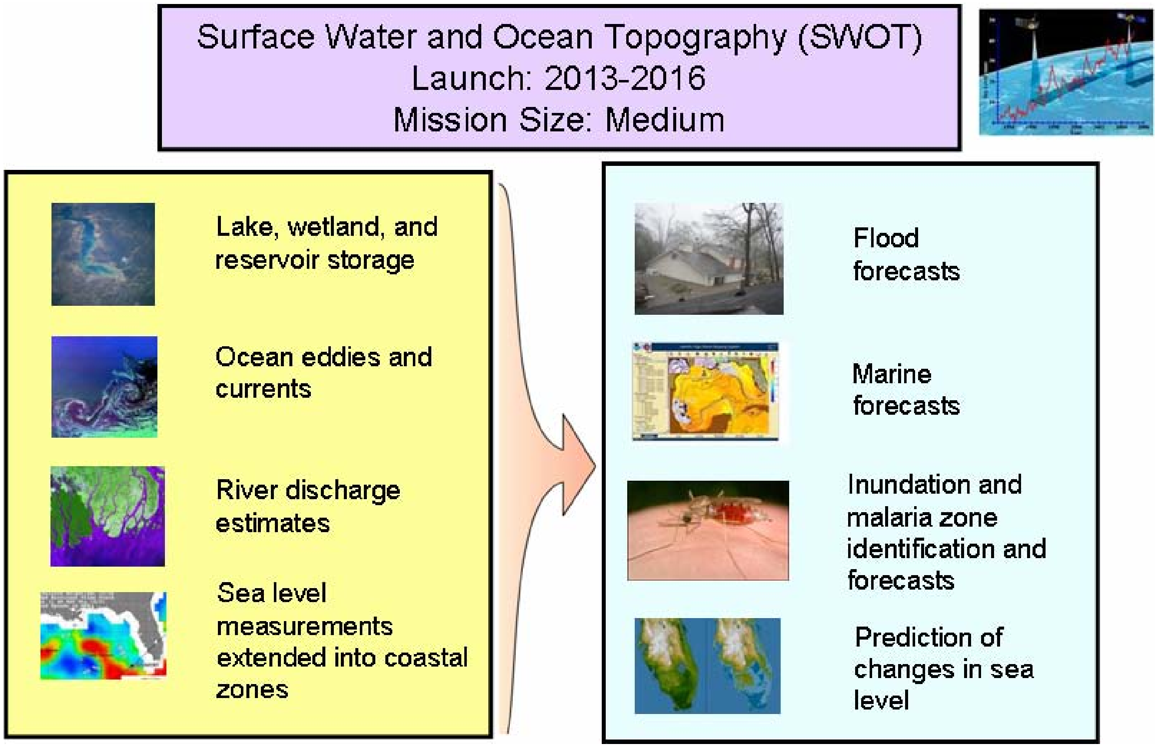
Further Discussion: Water Resources and Global Hydrological Cycle (Chapter 11) Section 11.3.1

Related RFI(s): Similar to the Hydros mission proposed for ESSP

Supporting Documents:

1 Soil Moisture Mission Working Group (SMMWG) Report, Version March 2006.
2 Entekhabi, D., Njoku, E., Houser, P., Spencer, M., Doiron, T., Smith, J., Girard, R., Belair, S., Crow, W., Jackson, T., Kerr, Y., Kimball, J., Koster, R., McDonald, K., O'Neill, P., Pultz, T., Running, S., Shi, J.C., Wood, E. and van Zyl, J., The Hydrosphere State (HYDROS) mission concept: An Earth system pathfinder for global mapping of soil moisture and land freeze/thaw. *IEEE Transactions on Geoscience and Remote Sensing*, 42(10), 2184-2195.
3 Entekhabi, D., G. R. Asrar, A. K. Betts, K. J. Beven, R. L. Bras, C. J. Duffy, T. Dunne, R. D. Koster, D. P. Lettenmaier, D. B. McLaughlin, W. J. Shuttleworth, M. T. van Genuchten, M.-Y. Wei, E. F. Wood, 1999: An agenda for land-surface hydrology research and a call for the second International Hydrological Decade, *Bulletin of the American Meteorological Society*, 80(10), pp. 2043-2058.
3 Leese, J., T. Jackson, A. Pitman, and P. Dirmeyer, 2001: Meeting Summary: GEWEX/BAHC International Workshop on Soil Moisture Monitoring, Analysis, and Prediction for Hydrometeorological and Hydroclimatological Applications, *Bulletin of the American Meteorological Society*, 1423-1430.
4 Joint DOD-NOAA-NASA Integrated Operational Requirements Document II (IORD-II), www.osd.noaa.gov/rpsi/IORDII_011402.pdf

Surface Water and Ocean Topography (SWOT)



Surface Water and Ocean Topography (SWOT)
Launch: 2013-2016
Mission Size: Medium

- Lake, wetland, and reservoir storage
- Ocean eddies and currents
- River discharge estimates
- Sea level measurements extended into coastal zones

- Flood forecasts
- Marine forecasts
- Inundation and malaria zone identification and forecasts
- Prediction of changes in sea level

Over 75% of the world's population depends on surface water for their primary source of drinking water. Yet there is no coordinated global observing system for surface water. Furthermore, in the case of trans-boundary rivers, information about water storage, discharge, and diversions in one country that affect the availability of water in its downstream neighbors is often not freely available. For rivers, the surface stage, or water level, is the most critical observation which allows estimation of river discharge, yet the global network of river discharge *in situ* observations is extremely non-uniform – generally the observation density is much higher in the densely populated portions of developed countries than in the developing world. The Surface Water and Ocean Topography (SWOT) mission would produce swath (image) altimetry of water surfaces over both the lands and oceans globally at much higher spatial resolution than is currently available. This information would extend the successes of ocean altimeters to inland and coastal waters, and would provide a basis for measuring directly the storage of water in lakes, reservoirs, and wetlands globally. River discharge would be estimated as a derived variable. River discharge is a key variable not only for water management, but for flood forecasting, which is the main tool for mitigation of property damage and loss of life from one of the most devastating natural hazards. Moreover, major health issues such as malaria are also linked to fresh water storage and discharge.

In addition to providing information about the distribution of surface water and its movement over land, the SWOT swath altimeter would also provide precision measurements to continue a climate record of sea level and to extend that record to coastal regions (including estuaries), where continued population growth and development pressures threaten marine resources. Bathymetry from a swath altimeter would improve navigation and marine rescue operations, planning for resource management, prediction of tsunami heights, and mixing rates in the deep ocean. The swath altimeter would help to improve climate and weather forecasts as well, by providing essential information on changes in ocean circulation and the contributions of ocean eddies to those changes. Changes in ocean circulation are related in large part to changes in wind forcing such that the coordination of sea level measurements with improvements in the observations of ocean vector winds will greatly enhance the measurements of either mission. Coastal ecosystems are greatly affected by changes in wind-forced coastal circulation and high resolution in both measurements will contribute to improved fisheries management. Hurricanes in the Gulf of Mexico have been shown to intensify over the warm Loop Current and its eddies, a system not well resolved by the current nadir altimeters. A similar issue of insufficient measurement detail currently confronts ocean-climate models. Improving such models could result in improved forecasts, and, in turn, mitigation of storm impacts on health and property.

Background: SWOT will address science and applications questions related to the storage and movement of inland waters, the circulation of the oceans and coastal waters, and the fine-scale bathymetry and roughness of the ocean floor. SWOT will consist of a swath altimeter that will produce measurements of water surface elevations over inland waters, as well as near-coastal regions and the open ocean. Over land, it will provide observations of water stored in rivers, lakes, reservoirs, and wetlands, with river discharge estimated as a derived variable. Surface water storage change and river discharge are major terms in the terrestrial water balance that are currently observed only at points with highly varying density globally. Spatial mapping of water surface elevations will capture the dynamics of wetlands and flooding rivers, which exert important controls on the fluxes of biogeochemical and trace gases between the land, atmosphere, and oceans. Over the ocean, the scientific value of past altimetry missions is well-documented for ocean circulation, tides, waves, sea level change, geodesy, and marine geophysics. However, spatial resolution issues have precluded the use of ocean altimeters in near-coastal waters. With the much higher spatial resolution that is facilitated by swath altimetry, SWOT is expected to produce information about bathymetry, tidal variations, and currents in near-coastal and estuarine areas as well.

Scientific Objectives: The wide swath altimeter will measure spatial fields of surface elevations for both inland waters and the ocean. These will lead to new information about the dynamics of water stored at the land surface (in lakes, reservoirs, wetlands, and river channels), and improved estimates of deep ocean and near-coastal marine circulation. These observations will provide the basis for estimation of the dynamics of water storage and river discharge variations. The SWOT altimeter will have a vertical precision of a few cm (averaged over areas less than 1 km^2)[12] and the ability to estimate surface water slopes to a precision of one microradian over areas less than 1 km^2. The latter will lead to an improvement in the spatial resolution of global estimates of ocean bathymetry by a factor of 20, which is expected to result in the mapping of ~50,000 additional sea mounts. The altimeter requires a precise (non-sun-synchronous) orbit for measurement accuracy, with a likely repeat cycle of about 21 days (combining ascending and descending orbits results in a revisit of about 10.5 days) and coverage to latitudes up to 78^o. For rivers, the goal is to recover channel cross-sectional profiles to within 1 m accuracy at low water which will allow estimation of the discharge of ~100 m-wide rivers via assimilation into hydrodynamic models. The resulting discharge estimates will constitute fundamentally new measurements for many parts of the globe where there is no *in situ* stream gauge network, or where the network is too sparse to estimate surface water dynamics at large scales. For the ocean, the mission will map sea level with precision of a few cm and a spatial resolution of less than 1 km^2 extending the sea level measurements to the ocean eddy field and into the coastal zones. With a nadir-looking altimeter, a non-sun-synchronous orbit, and precise tracking, the mission can extend the climate record of sea level beyond the current Jason series of altimeters.

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[12] Note that the assumption here is that the swath altimeter would use Ku band, however as discussed in Chapter 11 (section 11.3.2) trade studies will be required to decide between Ka and Ku band, the primary tradeoff being precision (higher for the shorter Ka wavelength) and data loss rates during precipitation (lower for Ku band)

Mission and Payload: A suite of instruments will be flown on the same platform: a Ku-band near-nadir SAR interferometer; a 3-frequency microwave radiometer; a nadir-looking Ku-band radar altimeter; and a GPS receiver. The Ku-band SAR interferometer (note that some variations have specified Ka band, which gives slightly better vertical resolution, but increased data loss in precipitating conditions) draws heavily from the heritage of the Wide Swath Ocean Altimeter (WSOA) and the Shuttle Radar Topography Mission (SRTM). The Ku-band synthetic aperture interferometer would provide vertical precision of a few centimeters over areas less than 1 km^2 with a swath of 120 km (including a nadir gap). The nadir gap would be filled with a Ku-band nadir altimeter, similar to the Jason-1 altimeter, with the capability of doing synthetic aperture processing to improve the along-track spatial resolution. Because the open ocean lacks fixed elevation points, a microwave radiometer will be used estimate the tropospheric water vapor range delay and the GPS receiver for a precise orbit. A potential side benefit is that the GPS receiver could in principle also be used to provide radio occultation soundings. Orbit selection is a compromise between the need for high temporal sampling for surface water applications, near-global coverage, and the swath capabilities of the Ku-band interferometer. A swath instrument is essential for surface water applications since a nadir instrument would miss most of even the largest global rivers and lakes. To achieve the required precision over water, a few changes to the SRTM design will be incorporated. The major one would be reduction of the maximum look angle to about 4.3^o which would reduce the outer swath error by about 14 times compared to SRTM. A key aspect of the data acquisition strategy is reduction of height noise by averaging neighboring image pixels, which requires an increase in the intrinsic range resolution of the instrument. A 200 MHz bandwidth system (0.75 m range resolution) would be used to achieve ground resolutions varying from about 10 m in the far swath to about 70 m in the near swath. A resolution of about 5 m (after onboard data reduction) in the along track direction can be achieved by means of synthetic aperture processing. To achieve the required vertical and spatial resolution, SAR processing must be performed. Raw data would be stored on board (after passing it through an averaging filter), and downlinked to the ground. The data downlink requirements (for both ocean and inland waters) can be met with eight 300 Mbps X-band stations globally.

Cost: ~$450M

Schedule: As a practical matter, the scheduling for SWOT may be dictated by the need for continuing ocean altimeter observations -- SWOT could satisfy the operational requirements of the Jason series (meaning that SWOT would essentially become Jason-3). Depending on the longevity of Jason-2 (currently scheduled for launch in mid-2008), this would suggest a SWOT launch date in the 2013-2015 range. Given the heritage of SWOT in WSOA and SRTM, the technology is sufficiently mature that such a schedule should be feasible. An overlap with XOVWM to measure winds is highly desirable for ocean applications.

Further Discussion: Water Resources and Global Hydrological Cycle (Chapter 11) Section 11.3.2

Related RFI(s): 79, 108

Supporting Documents:

Alsdorf D.E., E. Rodriguez, and D.P. Lettemaier, 2006: Measuring Surface Water from Space, in review, *Reviews of Geophysics*.

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Fu, L.-L., and A. Cazenave, editors, 2001: Satellite Altimetry and the Earth Sciences: A Handbook of Techniques and Applications, Academic Press, San Diego, 463 pp.

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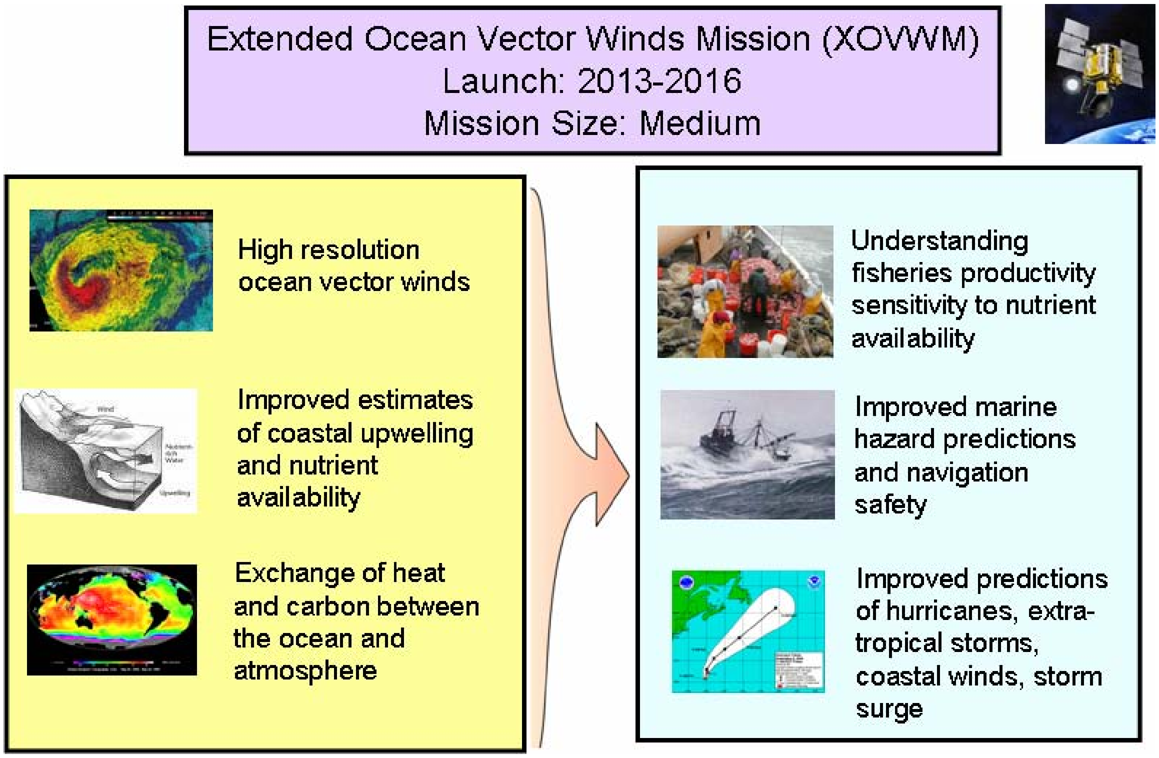
2004 "Bathymetry from Space" issue of *Oceanography* (http://www.tos.org/oceanography/issues/issue_archive/17_1.html)

Extended Ocean Vector Winds Mission (XOVWM)



Extended Ocean Vector Winds Mission (XOVWM)
Launch: 2013-2016
Mission Size: Medium

- High resolution ocean vector winds
- Improved estimates of coastal upwelling and nutrient availability
- Exchange of heat and carbon between the ocean and atmosphere

- Understanding fisheries productivity sensitivity to nutrient availability
- Improved marine hazard predictions and navigation safety
- Improved predictions of hurricanes, extra-tropical storms, coastal winds, storm surge

The scatterometer has been shown to be critical in improving marine warnings and hurricane forecasts. In fact, the NCEP Ocean Prediction Center has added a higher level of warning for ships ("hurricane force winds") for the mid-latitude ocean, based on improved wind measurements from QuikSCAT. The NCEP Tropical Prediction Center has found QuikSCAT to be critical for accurate hurricane forecasts and warnings.[1] Because the NPOESS sensor that would have measured ocean vector winds (CMIS) has been cancelled,[13] the XOVWM would be a key U.S. contribution to weather forecasting. In data assimilation studies and at ECMWF, scatterometer data have been demonstrated to improve storm center locations and intensity. High-resolution winds in the coastal region will also allow improved estimates of upwelling and the associated increases in nutrients for fisheries management. Use of winds to force coastal circulation models will improve estimates of currents, for such activities as search-and-rescue, shipping, and monitoring oil platform safety and oil spills, and thus contribute greatly to increases in safety and economic efficiency of these activities.

Coordination between the Surface Water and Ocean Topography Mission, which will provide high-resolution sea level measurements from a wide-swath altimeter, and the XOVWM will give the observations needed to improve our understanding and modeling of air-sea interaction and ocean circulation, particularly in coastal regions. We now know that we need higher spatial resolution in both winds and sea level to understand and predict the impact of warm ocean regions on hurricane intensification.

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[13] CMIS is being recompeted and will be replaced by a smaller-antenna, less technically risky, and less costly instrument tentatively known as MIS (Microwave Infrared Sounder). Trade studies to determine the specifications of MIS were ongoing as this report went to press Although NOAA officials have stated their intent for MIS to retain most of the CMIS capabilities to measure vector winds, the actual capabilities are unknown at this time.

Background: The Extended Ocean Vector Winds Mission (XOVWM) will address science and applications questions related to air-sea interaction, coastal circulation and biological productivity, improved forecasts of hurricanes, extra-tropical storms, coastal winds and storm surge, exchange of heat and carbon between the atmosphere and the ocean, and forcing of large-scale ocean circulation.

The XOVWM is derived from requirements by the Weather panel for horizontal winds and by the Climate Panel for sustained measurements over the ocean, as well as being a high priority for both the Oceans Community[2] and the NCEP Forecast Centers, [1] particularly in the light of the cancellation and planned recompete of CMIS on NPOESS. The XOVWM also addresses interests of the Panel on Land-Use Change, Ecosystem Dynamics, and Biodiversity to better understand coastal ecosystems, as well as the desire for improved air-sea fluxes by both the Climate and Water Resources and Global Hydrologic Cycle Panels.

The XOVWM will measure wind speed and direction (vectors) over the global oceans at high spatial resolution using a dual-frequency scatterometer. Past scatterometers have revealed the existence of energetic small-scale wind structures associated with ocean temperature fronts and currents and with coastal topography, and are currently used in operational weather forecasting and marine hazard predictions. By increasing further the spatial resolution of the winds XOVWM would extend the benefits of scatterometry to coastal regions where winds force coastal currents and where better wind forecasts would improve navigation safety. XOVWM would extend the coverage of vector winds into the rainy centers of hurricanes and storms and provide the twice-daily vector winds needed for weather forecasts

Upper ocean circulation is wind-driven, so that to the extent that XOVWM overlaps the Surface Water and Ocean Topography Mission, the two missions together allow a simultaneous study of the variability in winds and ocean currents, for example, to forecast the increases in intensity as hurricanes pass over warm ocean eddies, or to understand the complex interactions between fisheries and circulation in highly productive regions, such as the California Current. This synergy could well lead to advances in the representation of upper ocean processes and atmosphere-ocean coupling in climate and forecast models.

Scientific Objectives: The XOVWM mission has both operational and scientific objectives. The report from the NOAA Workshop,[1] which included participants from NOAA, NASA, DoD, universities, and the private sector, provides a detailed assessment of the currently operating ocean vector wind sensors and gives new requirements for weather forecasting needs. Although the workshop goal was to document how ocean vector winds are used currently and to consider NOAA's future needs, this report is responsive to concerns expressed in the Decadal Survey interim report[3] about evaluating the need to "launch the Ocean Vector Winds mission prior to or independently of the launch of CMIS on NPOESS." (The elimination of the CMIS instrument and plans to recompete the instrument were announced in June 2006, approximately a year after the release of the interim report.) The workshop findings are that the data from NASA's research mission QuikSCAT are fully integrated into routine operations of the forecast centers, and have made several measurable improvements, including tracking tropical cyclone center locations and size and improving coastal and swell forecasts. Desired improvements in wind measurements, relative to the QuikSCAT baseline, include improved wind vector accuracy in rain, higher spatial resolution, better coverage in coastal regions, and more frequent wind measurements.[1] Comparisons of existing and proposed measurement technology show that a next-generation scatterometer could best meet proposed new requirements and that is the prototype for the mission described here. One aspect of the new requirements that cannot be met by a single mission is the 6-hour revisit time (the time between successive measurements). Meeting this requirement will require multiple coordinated platforms, including the European Space Agency's operational scatterometer, ASCAT on the MetOp series, which gives one wind vector per day (at mid-latitudes) with a maximum resolution of 25 km.

The science objectives are to extend the high-resolution wind fields into the coastal region, to extend the climate measurement begun by previous sensors, and to provide observations to continue to examine the air-sea interaction associated with the small-scale wind features that are only observed by satellite sensors. QuikSCAT winds have revealed persistent small-scale wind structure that is coincident with temperature fronts and narrow ocean currents, as well as topography from nearby islands and coastal mountain ranges.[4] It is not yet understood the extent to which these features contribute to the exchange of heat and carbon between atmosphere and ocean. High-resolution wind data provides a basis for stimulating and assessing improvements in boundary layer parameterizations used in weather prediction and climate models. High-resolution winds also improve air-sea flux estimates, even without improving resolution in other atmospheric variables. Coastal currents and the coastal winds that force them, have intrinsically small scales. Coastal phenomena are not currently mapped by either scatterometer or altimeter, owing to low spatial resolution and contamination of the radar signal by nearby land. Increasing spatial resolution of both sensors will reveal relationships between ocean eddies and winds (such as those between hurricanes and the warm eddies of the Loop Current). With increased resolution the numerous scientific gains from these sensors can be extended to forcing and verifying the coastal circulation models that are essential to fisheries and coastal management.

The measurement objective is to obtain ocean vector winds at 1-5 km spatial resolution over a broad region (revisit time of approximately 18 hours), with direction and speed at least as accurate as that of the SeaWinds scatterometer on QuikSCAT and with improved coverage of coastal regions. Improvements in the accuracy of winds in rainy conditions is needed in applications such as hurricane prediction or improving prediction of ENSO, which depends on winds in the rainy Intertropical Convergence Zone.

Mission/Payload: The mission concept, which is based on input to the Decadal Survey, as well as simulations for a “next-generation OVWM” performed at the Jet Propulsion Laboratory, includes both active and passive sensors.[1] The dual-frequency scatterometer includes a Ku-band scatterometer that uses unfocused SAR processing to attain 1-5 km spatial resolution, as compared with the 12.5 km resolution of QuikSCAT. The Ku-band sensor would require a moderate size (2.5 m reflector) antenna. The mission would also include a C-band real aperture scatterometer, such as that currently used on the ESA scatterometers, to minimize the effect of rain and for better accuracy at high wind speeds. XOVWM also includes a multi-frequency passive radiometer with channels (SRAD as part of the scatterometer, K, and X-band) to improve wind vector retrieval, correction and estimation of rain. Wind accuracy specifications would include directional accuracy of <24 degrees at 2 km resolution (or <6 degrees at 12.5 km) for wind speeds 5-83 meters per second. The swath width would be approximately 1800 km wide. The nominal 800 km altitude orbit allows the possibility of sharing a platform with other missions, subject to power constraints. Because of the importance of XOVWM to weather forecasting and the importance of minimizing data latency, close coordination is needed between research and operational aspects of the mission, particularly with respect to ground operations and data flow.

Cost: ~$350M

Schedule: The scatterometer’s critical contribution to weather forecasting suggests an early launch to replace the aging QuikSCAT scatterometer; however, for studies of air-sea interaction, the scatterometer mission needs to be concurrent with the wide-swath altimeter mission (Surface Water and Ocean Topography) for at least two years, which suggests a launch in about 2014. Local overpass times should be coordinated with other proposed ocean vector wind missions, such as ASCAT to minimize the revisit times.

Further Discussion: Climate Change and Variability (Chapter 9) Section 9.3.1.4; Weather Science and Applications (Chapter 10) Section 10.3.1.2

Related RFI(s): 56, 79, 91, 98, 108

Supporting Documents:

1 NOAA Operational Ocean Surface Vector Winds Requirements Workshop, National Hurricane Center, Miami, FL, June 5-7, 2006, editors: Paul Chang and Zorana Jelenak.
2 Oceans Community Letter, sent to the Decadal Survey 1 May 2006, editors: Dudley Chelton and Michael Freilich (753 signatories). http://cioss.coas.oregonstate.edu/CIOSS/letter.html
3 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.
4 Chelton, D.B., M.G. Schlax, M.H. Freilich, and R.F. Milliff, 2004: Satellite measurements reveal persistent small-scale features in ocean winds, Science, 303, 5660, 13 Feb. 2004, 978-983.
5 Satellite Observation of the Climate System: The Committee on Earth Observation Satellites (CEOS) Response to the Global Climate Observing System (GCOS) Implementation Plan (IP), September 2006.

Part III:

Reports from the Decadal Survey Panels

5
Earth Science Applications and Societal Benefits

Increasing the societal benefits of Earth science research is high on the priority list of federal science agencies and policy-makers, who have long believed that the role of scientific research is not only to expand our knowledge but also to improve the lives of Americans. Although promoting societal benefits and applications from basic research has been emphasized in national science policy discussions for decades, policy and decision makers at federal, state, and local levels also increasingly recognize the value of evidence-based policy making, which draws on scientific findings and understandings.

Our theme in this chapter is the urgency of developing useful applications and enhancing benefits to society from the nation's investment in Earth science research. Accomplishing this objective requires an understanding of the entire research to applications chain, which includes generating scientific observations, conducting research, transforming the results into useful information, and distributing the information in a form that meets the requirements of both public and private sector managers, decision-makers, policy-makers, and the public at large (NRC, 2001; NRC, 2003). There are a number of remarkable successes in reaping the benefits of Earth science research. For example, Chapter 11 documents that many nations of the developed world have created sophisticated flood forecast systems that use precipitation gauges and radars, river stage monitoring, and weather prediction models to create warnings of floods from hours to several days in advance. However, there is no global capacity to do this, and developing nations are largely without this capability.

In many cases these successes have largely evolved through serendipitous opportunities for research applications rather than through a systematic, coordinated process. As a response to this concern, we offer observations on how to move from discovery to design, balance mission portfolios to benefit both research and applications, and establish mechanisms for including the priorities of the applications community in space-based measurements.

HOW DO WE PROGRESS FROM SERENDIPITY TO DESIGN?

We are limited in how we can advance the application of Earth science research and observations in the public and private sectors by several factors, including (1) inexperience in identifying the requirements of applied users of the data and information, (2) limited knowledge of the ways that managers, policy- and decision-makers, and the public obtain data and information and the ways they use them, and (3) the capacity of institutions and organizations to apply new types of data and information to traditional and ongoing processes and ways of doing business.

Earth science can contribute to societal benefits and more effective decision-making in multiple ways. It provides information that can be used to identify emerging problems, trends, and changes. In addition, research and observations permit managers, analysts, and decision makers to monitor ongoing phenomena. Third, these resources can be used to forecast and project future trends, and by so doing, permit managers, policy- and decision-makers to anticipate problems so that they can be addressed at an early stage. Finally, scientific data and observations also permit those who inform decision makers to test and evaluate future scenarios of possible outcomes. The challenge is to make the scientific information relevant, available, adaptable, and easy to use so that informed and knowledgeable choices can be made.

If Earth scientists are to foster applications and extend the societal benefits of their work, they must understand the research to applications chain, which includes understanding societal information needs, conducting research on the uses of information, generating relevant scientific observations, transforming the results into useful information, and distributing that information in a form that is understandable and meets the needs of both public and private sector managers, decision-makers, and policy-makers (NRC, 2001; NRC, 2003).

Identifying Requirements

We know that Earth science information can confer tangible and measurable benefit in myriad applications in addition to those identified in Chapters One and Two of this report. For instance, some highly detailed studies of the value of Earth science information seek to characterize how it is used and then quantify its benefits in various industrial sectors of the economy. These studies typically (although not exclusively) conduct empirical estimation in which benefits are defined and measured in terms of increases in output or productivity in the relevant economic sector (a detailed review of these studies is in Macauley, 2006). Examples include studies of the value of Earth science information for forecasting crop size and health (Bradford, 1977), geomagnetic storms and their impact on the electric power industry (Teisberg, 2000), the markets for agricultural commodities (Roll, 1984) and raisins (Lave, 1963), the economic damages of deforestation (Pfaff, 1999), and reducing the social risks and costs of natural disasters (Williamson, 2002).

At a more fundamental level, in the application of Earth science information, it is essential to know more about patterns of information seeking and information use both inside and outside the scientific community. This will involve research on where the primary information consumers in an organization are located and how they relate to those who have the power to set the agenda and make policy decisions. It will also involve identifying both routine management information needs and policy-making information needs. Finally, it will require that scientists understand the functions and patterns of agenda setting in both organizations and society. A multi-disciplinary research approach, linking natural and social scientists in studies of organizations and the interactions in the scientist-data-decision maker interactions, will provide better insights. Both NOAA and NASA have periodically supported research of this type, focused on communication and the utility of scientific information for non-traditional users of Earth science observations.

The successful involvement of both scientific and operational agencies in this process can be examined through research focused on how applications have been most *usefully* developed in the past and transmitted into operational domains. As earlier chapters in this report have emphasized, the field of weather and climate prediction demonstrates several examples of transitioning from research to operations. The satellite era opened in the late 1950s with the launch of Sputnik and the realization that this technology could be used to make observations of planet Earth. In the early 1960s, the major challenge was to learn to use scientific research and observations to improve weather forecasting skill and extend the valid time period to a few days. The Global Atmospheric Research Program (GARP) was launched in 1974 with this objective. The vision for this program was to work towards a global weather experiment, using a mix of geostationary and polar orbiting satellites, ground- and ocean-based measurements, and computer processing technology, brought together through scientific analysis. This experiment was conducted in 1979-1980 as a global initiative, and since then, global weather forecasting has continued to improve markedly. The transition of this scientific approach and related technologies to operational benefits took place because this objective was built into the vision, and because the societal value and benefits were recognized in advance. The scientific program went forward with the full participation of the operational agencies, and they were integral parts of the scientific team.

Another example of a successful research to operations transition is in measuring the interannual variability of the tropical ocean-atmosphere system. The El Niño events of the 1970s and early 1980s led to the design and implementation of the Tropical Ocean-Global Atmosphere Program (TOGA) in 1985 as a ten-year focused research program. The research observing system of ocean arrays and satellites was transitioned to operational support in the 1990s. The benefits of being able to predict the occurrence of El Niño and its impacts, and the development of effective response strategies that reduced the impacts had become evident. There was strong national and international pressure to maintain the capability to continue to provide these benefits. In each case, there was an identified public benefit and involvement of operational organizations from the beginning. The operational partners, mainly the national weather services, were clear, and they had well-established links with the user community. There was strong national and international support for the project, and there was strong leadership.

These examples demonstrate that recognition of the need for an operational organization that has a close relationship with the user community is essential in developing applications that can deliver lasting or ongoing benefits. An example where this has been difficult to achieve is in the efforts to develop the capacity for forecasting the physical state of the open oceans. Although weather forecasting as a national activity and the need for global information to make it effective for national interests are both well established, the case for open ocean prediction is not as clear. Although progress is being made, the transition of the research results from, for example, the World Ocean Circulation Experiment (WOCE) to an operational ocean prediction system, delivering information to a broad base of public users has been slower to take place.

The lesson here is that unless there is sustained institutional support for interactions between the scientific producers and the applications users of information, there is a risk that even successful examples of Earth science applications become "one-off" experiments that are not repeated over time. Of the examples identified in the previous section, for example, only those involving weather forecasting had institutional mechanisms designed specifically to foster such two-way interactions. In the other cases, the two-way interactions occurred early in program development through the activities of principal investigators, but there is no clear institutional mechanism to ensure that improvements in observations, methods, or changing needs can propagate through the systems.

In sum, to be successful, the use of Earth science data for applications of benefit to society will require research as well as data. Such research will improve our understanding of successful transitions from research data to societal applications, processes of information adoption and use outside the scientific community, and decision-making under uncertainty. It will also require sustained communications with potential users of scientific information.

Access to Data

Given the breadth of responsibilities of public and private managers and decision-makers, the use of potential applications from the Earth sciences will depend on having easy availability to data that are "accurate, affordable, and accessible" (NRC, 2003, p. 62).[1] Many of the decision-makers and other interested parties who need access to Earth science observations and information for addressing important environmental issues are unlikely to be highly-trained Earth science researchers. Non-scientists who use Earth science data and information must have a convenient and intuitive means of access to observations that are relevant to the problem they are addressing.

Improving data and information availability and accessibility should include establishing and adopting standardized data and information management practices that foster use and can be understood by the non-scientific user. Elements of data access and management that need to be addressed include the following:

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[1] One of the early examples of providing public access to scientific data for policy- and decision-making was initiated by President Herbert Hoover and eventually published as a 1700-page volume in 1933, during the Roosevelt administration. See *Recent Social Trends*, edited by W.F. Ogburn (New York, 1933). Unfortunately, this effort was not repeated and its impact was limited.

1. The management of Earth observations for operational applications and societal benefit begins with the existence of credible, professionally managed data records. The rapid pace of innovation in both information management technologies and observational technologies means that data management must be given high priority by scientists and funding agencies to avoid loss of the data in the future. This involves the use of community accepted metadata standards, repeated integrity checks of the data, and regular upgrades of data management hardware and software. (For a discussion of this issue, see the recent report by the International Council of Science, ICSU 2004.)
2. Potential applications developers will need some combination of baseline, status, and trend information. In general, applied users of Earth science data and information will find repeated observations of the same phenomenon over time to be more useful than data for a single point in time. Baseline data, however, can play a role in diagnostic analyses.
3. The establishment of permanent data archive and dissemination centers will be needed. Such centers will provide access to the data and serve as a critical source of individuals who have experience in the use of the data and can provide advice and counsel for new applications. It will be necessary to provide continuing institutional support for the data management and archiving processes. Moreover, because the value of the data increases over time, the cost of providing these facilities needs to be guaranteed over long time periods.
4. Finally, there will be a continuing need for education or training of new users of the data on how to obtain data, what they mean, and how to use them. There will be new generations of applications over time that will be created by people who need instruction in how to use Earth science data. In addition, new generations of decision makers will need to be educated about the societal benefits of Earth science data and information. Providing information about the data and training in its use will be an ongoing educational process that cannot be neglected.

The commitment to effective data management that meets the requirements of both scientific and non-scientific data users is critical to advancing the development of applications that benefit society.

Enhancing Applications Capability

The opportunities, and challenges, of using Earth observation data for practical applications were the topic of a set of three NRC/SSB studies during 2001-2003. One of the studies, *Transforming Remote Sensing Data into Information and Applications*, emphasizes the failure to fund development of applications and the lack of recognition accorded the development of applications among researchers and the journals in which they publish (NRC, 2001). The lack of financial and professional incentives to pursue and develop applications will limit the involvement of many scientists and could make it very difficult to realize societal benefits from the Earth sciences. For this reason, it is important that there be an appropriate level of funding for applications, including public sector applications at all levels of government, private sector applications, and not-for-profit or non-governmental applications. It is essential as well that professional recognition of the value of advancing societal benefits be part of the decadal vision and its implementation.

The capacity of applied users to take advantages of the availability of new sources of Earth science data and information for societal benefits is also dependent upon cultivating broad institutional and organizational capacity among potential applications users. One of the Space Studies Board reports, *Using Remote Sensing in State and Local Government: Information for Management and Decision Making* (NRC, 2003), pointed out that the use of remote sensing data in management and policy problems in state and local governments depends on institutional, leadership, budgetary, procedural, and even personnel factors in the organization. Although they are often ignored, the role of these institutional factors in the applications process should not be underestimated.

Supporting an Informed Citizenry

A continuing benefit of the nation's investment in the Earth sciences is the potential for improving the communication of Earth science results and teaching of these fields in the formal educational curriculum. The Earth and space sciences have a central role to play in creating an informed and scientifically-literate citizenry, particularly with regard to natural hazards, resource use, and environmental change. Satellite imagery and visualization technology and tools have revolutionized how we view the Earth, its systems and processes and the relationships between people and the natural environment. In addition, the synoptic view of the Earth available through remote sensing images transcends political boundaries and enhances students' understanding of the planet. Used as teaching tools, satellite information and visualizations can help learners of all ages develop more effective skill in critical thinking and problem solving and can contribute to a better educated workforce.

Fully realizing societal benefits requires us to enhance understanding among applied users and cultivate appropriate institutional and educational capabilities in organizations that are potential users of applications, and among the agencies that produce the underlying data and supporting science. There is a need for devising professional rewards for those who develop and sustain applications and societal benefits.

BALANCING THE MISSION PORTFOLIO TO BENEFIT BOTH RESEARCH AND APPLICATIONS

As this report has emphasized, benefits accrue to the Earth sciences both from gains in scientific research and from the application of scientific information in decision-making. However, the measurement needs for particular scientific research topics and related applications have the potential to be significantly different. For example, consider the state of measurements in land remote sensing, as summarized in Chapter 7. The importance of the Landsat-class measurements in establishing a long-term baseline of land-cover measurements cannot be overstated. The sequence of instruments from the Multispectral Scanner (MSS) to the Thematic Mapper (TM) to the Enhanced Thematic Mapper + (ETM+) are the longest, best-calibrated time series of any biophysical time series of the Earth. They are clearly essential for research, applications, and operational uses. However, newer measurements of the Earth's land-cover typically fall in one of three different dimensions – higher spectral resolution measurements of surface reflectance with high temporal resolution (MODIS and VIIRS), hyperspectral resolution imagers (as proposed in Chapter 7), or the very high spatial resolution imagery of the private sector's missions, such as QuickBird, familiar around the world now to users of Microsoft Virtual Earth or Google Earth. Such missions and measurements emphasize different components of measuring the characteristics of the Earth's land-cover, each according to its desired use. Although each category of mission measures fundamental properties of the Earth's land-cover, each optimizes its measurements differently according to the needs of the dominant user communities. As a result, they are not, for the most part, substitutable for each other, but instead complement each other.

An overall Earth science strategy that merges scientific research and societal application must acknowledge that different research and operational applications will require different approaches to measurement, and provide a means of optimizing potential benefits against available resources for the total observing system. The desired means would involve defining the specific research and application goals of a potential measurement, evaluating the degree to which existing or proposed measurements support those goals, and developing an optimal implementation strategy that balances overall cost against achievement of the requirements.

The design of space-based measurements that are tailored for particular applications is an important first step in achieving societal benefit. Developing the requirements for a given application involve both better understanding the scientific issues as well as the decision-making context within which the targeted measurements play a role.

The committee recommends that future Earth Science mission strategy development include social science research into the key drivers of measurement need for societal decision-making.

Extracting societal benefit from space-borne measurements requires, as an equally important second step, the development of a strong linkage between the measurements and decision-makers who will use such measurements. This linkage must be created and sustained throughout the lifecycle of the space mission. In order to implement future missions, scientists who are engaged in research that is intended to have both scientific and societal contributions must operate differently than they did in the days when the advancement of science was the primary/only goal of research. Applications development places new responsibilities on agencies to balance applications demands with scientific priorities. The character of missions may change in significant ways if societal needs are given equal priority with scientific needs. For example, scientists interested in measurements of the solid-Earth that are relevant to issues associated with protection from, or early warning of geological hazards, as emphasized in Chapter 8, should work directly with the natural hazards community in order to ensure that the measurements and data management systems that they propose are indeed useful for protecting property and lives, as well as for their scientific interests. Box 5.1 lists guidelines that, if routinely incorporated in mission planning, would foster such a balance between research and applications. Box 5.2 lists a series of questions which should be considered as part of any mission planning activity. They emphasize the end-to-end nature of applying Earth science observations to important societal issues.

The potential societal benefit of a measurement will depend in large degree on how well these issues have been understood and addressed in the proposal, its evaluation, and the implementation of the mission.

BOX 5.1 GUIDELINES FOR MISSION PLANNING TO BALANCE SCIENCE AND APPLICATIONS

- Processes to move from observations to data to information should be identified in the initial planning process for new missions.
- Mission planning should consider performance requirements for applications, such as timeliness and capacity for data integration.
- Planning should consider the need for and availability of ancillary data.
- Planning and implementation priorities should include the need to link the data to models and decision support tools and processes.
- Planning should include ensuring that the ancillary data are there when needed
- Planning should provide effective lines of communication between decision-makers and data gatherers.

BOX 5.2 QUESTIONS FOR PLANNERS IN INCORPORATING APPLICATIONS WHEN SETTING PRIORITIES FOR MISSION SELECTION

- What is the immediate need? What is the projected need?
- Has an analysis of benefits been done? Who are the beneficiaries? How does information from the measurement reach them?
- What alternative sources of information exist for the application? *In situ* sources? Foreign sources? Is the proposed measurement/mission a measurable improvement?
- To what degree does the application need to be operational/continuous? Can it be a periodic or a one-time measure?
- What are the requirements for timeliness in terms of delivery of products?
- What are the means for funneling data to decision-makers, either directly or indirectly through data brokers (e.g. Weather channel) or interpreters (e.g. NGOs)? What is the commitment on their part to use the data/information?
- What are the necessary ancillary data? How are they to be made available?
- Are necessary simulation/analytic/visualization tools in place?
- What is the weakest link in the chain from measurement to use?
- What are the risks if this is not done?

MECHANISMS FOR PRIORITIZATION OF SPACE-BASED MEASUREMENTS BY THE APPLICATIONS COMMUNITY ARE NEEDED

All the examples from the sections above demonstrate that societal benefits can indeed be generated from the use of satellite observations, even though those benefits are not well quantified in all cases. But in only a very few cases is there any process for ensuring that either intermediate or end-user communities are able to have their requirements enter federal agency planning cycles as those agencies decide how to improve their observational capabilities or plan for new ones. A feedback loop is often missing in a formal way, and in particular, applications communities that are newly developing or in which the user communities lack institutional structure as, for example, is in place within the weather forecasting community, are left with *ad hoc* processes for influencing agencies' plans for new or improved observations. For example, new measurements for applications in weather forecasting can be evaluated within the existing structures of NASA and NOAA because those agencies have for the most part worked out the processes by which the importance of such measurements can be evaluated, notwithstanding the known difficulties of transitioning new measurements to operations. However, new measurements for land-cover, geological hazards, or water resources, to mention just a few, do not have existing relationships between client agencies and the space agencies that naturally lead to evaluation of their potential for applications. New measurements that would be relevant to such critical issues as deforestation and the loss of biological diversity or interruption of ecosystem services essentially have no client agency, and must rely individual university researchers or staff in non-governmental organizations to lobby the space agencies, without benefit of strong institutional ties to those agencies.

The space agencies must additionally incorporate new private partners in their efforts to strengthen the science and applications of Earth observations. The rise of the private sector in using imagery or other remotely sensed data of all sorts in a variety of marketed applications is a relatively recent phenomenon, compared to the history of the U.S. space program. But the commercial success and popularity of such endeavors as Google Earth and Microsoft Virtual Earth point to the fact that there are large and essentially untapped markets of private users for Earth observations, as well as users among the scientific and public institutions. We are now seeing, for the first time in the remote sensing community, the private sector performing both essential data acquisition (e.g., hyperspatial resolution imagery) and essential data applications (e.g., Google Earth and other mapping and geospatial information services) tasks, essentially without governmental intervention. Yet even these endeavors cannot hope to maintain the levels of investment in R&D necessary to sustain progress in our understanding of the evolving dynamics of the Earth system.

SUMMARY

The panel is certainly aware that it is raising new challenges for research and operations in the Earth sciences, and that existing models for how these might be implemented are scarce. The processes that would lead to a successful research program that emphasizes both scientific discovery and benefits to society need to be strengthened. In addition, agencies implementing missions will require a research and development system that can enable the large capital investment in space hardware and data management to fulfill its stated intentions in applications for social benefit. Agencies will also have to ensure that the missions that they sponsor and the associated research have the longevity to enable learning by their user communities; likewise, they have to learn to listen to the needs and desires of new user communities, and ensure that both stakeholder and advisory processes are in place to enable sufficient feedback to occur for the benefit of both users and data providers.

Because no one space agency or its partners can hope to encompass the full range of the measurements to applications chain, interagency coordination will certainly be required to enable the larger effort to “exceed the sum of its parts” in fully realizing benefits. There are likely to be needs for interactions among staff with different types of backgrounds and training that are difficult to foresee now, but that will demand new interdisciplinary relationships to be built. In addition, agencies will need to build new evaluation and incentive processes into their research programs to ensure that there is sufficient attention paid to the importance of societal benefits (Box 5.1). These issues are consistent with those identified in many earlier NRC reports that emphasize the interdisciplinary challenges of developing Earth system science.

Finally, systems of program review and evaluation will need to be revamped to make our vision of concurrently delivering societal benefits and scientific discovery come into being. Numbers of published papers, or scientific citation indices, or even professional acclamation from scientific peers will not be enough to evaluate the success of the missions we have proposed. The degree to which human welfare has been improved, the enhancement of public understanding of and appreciation for human interaction with and impacts on Earth processes, and the effectiveness of protecting property and saving lives will additionally become important criteria for a successful Earth science and observations program.

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6
Human Health and Security

OVERVIEW

Virtually every aspect of human health and well-being is linked to our earth, be it through the air we breathe; the climate or weather we experience; the food we eat; the water we drink; or the environs in which we live, work or recreate. Diverse environmental factors affect the distribution, diversity, incidence, severity, or persistence of diseases and other health effects—something that has been recognized for millennia. Yet in the United States today, an estimated 1.8 to 3.1 years of life are lost to people living in the most polluted cities due to chronic exposure to air pollutants (Pope 2000). Roughly 9 million cases of waterborne disease occur in the United States each year (Rose et al. 2001). Exposure to ultraviolet (UV) radiation may be the most important preventable factor in determining a person's risk for skin cancer in the United States (American Academy of Dermatology, 2006) among the more than one million new cases that occur each year (American Cancer Society, 2006a). The 1995 heat wave in Chicago claimed nearly 700 excess deaths (Whitman et al. 1997), and perhaps as many as 15,000 people died in 2003 during a prolonged heat wave in France (Fouillet et al. 2006). The annual number of industrial accidents involving the release of hazardous substances from facilities required to have risk management plans ranged from 225 to more than 500 over the nine-year period ending in 2003 (EPA 2005). Although diseases transmitted by arthropod vectors (mosquitoes, sand flies, etc.) may be less important in the United States than elsewhere in the world, they still represent an important health concern. In developing countries, malaria kills each year from 1-2 million people, and dengue fever annually afflicts as many as 80 million people globally (Pinheiro and Corber 1997). These are several of the important examples identified by the Panel on Human Health and Security, and discussed later in this chapter. The examples critically link observations of the earth's environment to human health and security risks, and indicate the opportunities that space-based observations offer to better assess and manage those risks.

The current unprecedented rate of global environmental change and the growing rates of global population growth and resource consumption indicate that analyses of such changes are important to human well-being. Global movement of people, pollutants, and lifestyles has exacerbated the role of environmental factors that affect human health. The urgency of obtaining global data–often obtained via space-based methods–on land-use changes, climate changes, weather extremes, episodes of atmospheric and surface water pollution, and other observations has become critical to understanding how population and economic changes throughout the globe affect our common well-being. The panel considered issues of environmental factors critical to its charge, and began by identifying various kinds of human health and security risks as important in developing the panel's recommendations. The panel then evaluated how remote sensing data from space might contribute to a better understanding of relationships between those factors and risks.

Over the past couple of decades, health and environmental scientists have used remote sensing data in diverse analyses of how environmental factors have altered risk of various health effects in time and space, and how these insights might eventually be used to make observations and evaluate and manage risk. The basis for such research is in the long-term availability of remote sensing data, combined with *in situ* observations (such as disease surveillance and reporting) that permit analyses necessary to uncover patterns and develop forecasts (NRC 2006). Such research is impossible without continued capture and dissemination of remote sensing data, information that has served as the basis for understanding many larger-scale spatial environmental patterns. These data, combined with *in situ* epidemiological observations of disease morbidity and mortality, have served as the mainstay of environment-disease research and recommendations related to human health and security. Many studies successfully demonstrate application of remote sensing data to spatial or temporal variation in disease incidence, or the assessment of quantity or quality of air, food and potable water, for example. The aim of such studies typically is either enhancing forecasts of future outbreaks or understanding pathways by which environmental features are linked to increased health risks. While the research being undertaken has been productive in identifying environmental links to human health risk, the forecasting confidence for most diseases and other health effects is still very weak. For this reason, the continued availability of space-based observations of land use/land cover, oceans, weather/climate and atmospheric pollutants is critical to further enhancing the understanding of links to diseases, but also to expanding early warning capacities of times and places where risk is elevated. This will be possible only though analyses of long-term time series. Only then will an understanding of such patterns be useful to risk managers and health responders.

In general, knowledge of changing risk across regions and habitats, or over weeks to a few years, should improve forecasts, hence detection capabilities and possible interventions and adaptation. For example, new higher-spatial-resolution satellite data may increase understanding of some infectious diseases where risk is influenced by changes in microhabitat conditions. Also, such data can enhance understanding of relationships between human health effects and UV radiation dosage levels. Likewise better remote sensing capabilities should enhance the capacity to detect and track risk agents including local drought conditions, harmful algal blooms, regional air pollution, and many acute releases of environmental contaminants. Anticipated health and security benefits currently drive most of the basic research agenda that employs space-based observations, yet public health practitioners and risk managers are only slowly expanding their use of these results. Future research is more likely to be useful if it is closely linked with the needs of the public health community, risk mangers, emergency responders, and specific components of human well-being.

Prioritization of Needs

The approach taken by this panel was somewhat different than that of most other panels, in that we intentionally began by identifying important health threats that are related to environmental factors and desired health outcomes (societal benefits). We then identified the kinds of earth observation parameters and variables (environmental data) that we considered important to informing relevant research and applications, and finally determined which platforms, sensors and remote sensing data could provide the appropriate data (missions). Thus, the panel's discussions were focused on various kinds of health effects and the earth environmental factors and contaminants that may contribute to those effects. The discussions also focused on determining which people are at risk and where and when the risk occurs. Thus, mission recommendations from this panel correspond to those of many of the other panels, in that climate, weather, ecosystems, and water resources, in particular, directly and indirectly affect the range of human health and security issues that are identified here. This approach led to the following considerations:

- A simple prioritization of which sensors, platforms, or missions are most essential to human health and security is difficult to create. The importance of existing and future sensors depends on the environmental health effects that our society considers to be of greatest concern which, in turn, determines the environmental data that best informs exposure and risk assessments, and efforts to predict and prevent or mitigate ill-health effects.
- At a minimum, continuity of existing sensors is critical to developing observational and forecast capabilities for most diseases and other health risks. Although environmental links with more

direct, short-term health effects are reasonably well understood (e.g., temperature and heat stress; atmospheric pollutants and some respiratory symptoms), many other environment-disease associations involve complex pathways requiring extensive time-series analyses to develop sound predictive associations.

- Continued research is needed to firmly establish the predictive relationships between remotely sensed environmental data and patterns of environmentally related health effects. Beyond these research needs, preservation of existing sensors (e.g. AVHRR/MODIS, Landsat) will permit continued development and institution of early warning or detection capacity for some better-understood limits between environmental exposures and health effects.
- The research agenda of many human health and environmental scientists who analyze remote sensing data and *in situ* data increasingly involves time-space modeling and statistical analysis of associations, suggesting that federal agencies should vigorously support such efforts. Accordingly, enhanced funding for research and application of space-based observations to health problems should be an important part of NASA's and NOAA's missions to produce societal benefits.
- Field evaluation of analytic results and forecasts is important to developing more comprehensive and accurate models of diverse complex environment-disease dynamics. Such efforts may eventually serve as a basis for developing improved observation systems.
- The need for higher spatial resolution data depends on the health problems to be addressed. Exceptions to this may be where global transport of risk agents (water or air plumes; migration of birds) could be monitored by multiple sensors over large areas. Many health applications of remote sensing data will employ data relevant to applications identified by other panels (e.g. weather, climate, ecosystems, and water). We recognize an important synergy between many of the recommended data needs for our panel and those of other panels.

Overarching Issues

The World Health Organization defines health as "…a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." Thus, human health and security should be thought of in the larger context of multiple factors that influence people through various direct and indirect pathways. The earth sciences agenda that relates to human health involves at least how environmental factors affect the more limited notion of human health. However, the manner in which these factors help shape and define social, economic, and psychological aspects of people's existence also alter health. For these reasons, the value of remote sensing data can not be considered independent of that involving the more encompassing meaning of health and security, nor of data coming from other sources concerning demographic, occupational, insurance, housing, and other surveys and analyses.

By recognizing this, the panel considered the overarching issues to involve much more than those of the more narrow conceptions of human health. Indeed, we considered that the societal benefits accruing through improved human health should be fundamental to defining the research and applications goals of the earth science agenda. These include the need for an intellectual framework that directs bridging research between the earth system framework and the public health response and decision-maker community. It is critical for earth scientists to interact more openly and effectively with public health and security officials, to help determine the needed understanding, the desired analyses, and the applications through which remote sensing data can contribute to prediction, detection, and mitigation of threats to health and security. With such conceptual, research, planning, and policy interactions, the earth science community, and NASA and NOAA will be better able to contribute to improving human health and security, thus achieving the desired societal benefits. Developing such a reliable observational and predictive capacity, based on remote sensing data used in the context of human health risk, should be a goal of future space mission decisions and agency responsibilities.

Critical Questions

Given these contextual issues, the panel discussed the following questions, among others that were part of our charge:

- How can remote sensing data be enhanced to assist detection and prediction of the places where disease risk is elevated or times when disease outbreaks are likely?
- Might such data enhance the rapid detection of events that threaten health or security?
- How can risk maps derived from space-based observations be used to enhance public health efforts directed at education and prevention?
- What new exchanges can expand interactions between remote sensing system designers and public health analysts that will help identify spatial and temporal risk patterns?
- What new understanding derived from remote sensing data can be used to target interventions aimed at reducing vulnerability of human communities to health risks?

STATUS AND REQUIREMENTS

Status of Current Understanding/Strategic Thinking

To understand the importance of space-based observations in addressing human health and security, we provide a few examples of past efforts, discuss the need to assimilate space-based observations with other data sources, identify the role of spatial and temporal scale, and stress the importance of moving research toward operations.

Uses of Space-based Observations for Addressing Human Health Concerns

In addressing human health and security concerns, space-based observations are most useful when used along with many other sources of data. Public-health and risk management decision making has benefited from space-based technologies, and can benefit further with improvements in these technologies, through applications that include:

- *Prediction of occurrence of disease or disease outbreaks:* Space-based observations provide spatial and temporal data on environmental changes that affect the conditions related to disease occurrence and can be combined within predictive frameworks to forecast health emergencies.
- *Rapid detection and tracking of events:* Given sufficient temporal or spatial detail, space-based observations can provide data to support rapid detection of environmental changes or pollution events that affect human health.
- *Construction of risk maps*: The spatial extent of space-based observations provides a means to identify spatial variability in risk, potentially improving the scale of environmental observations such that they match the scale of activities in human communities.
- *Targeting interventions*: Activities to reduce the vulnerability of human communities to health risks, including environmental, behavioral, educational, and medical interventions, can be guided, improved, and made more efficient by employment of available and proposed space-based observational systems.
- *Enhancing knowledge of human health-environment interactions:* Basic research on the causes of disease is on-going, and remote sensing of environmental parameters that affect health is crucial for investigations that improve our understanding of the spatial and temporal dynamics of health risk.

Assimilation of Space-based Observations with Other Data Sources and Models

Space-based observations are most effective as inputs to public-health decision making where they are used in concert with other data systems, including ground-based observations of environmental and epidemiological conditions, demographic data, data collected from aircraft, and outputs from numerical models.[1] Investments are needed for the coordination of data collection efforts from multiple sources for specific purposes. Specifically, research on public-health decision support systems needs to address the limitations in how current data systems interface, and the opportunities for coordinating observations.

The Importance of Appropriate Spatial and Temporal Resolutions

Effective incorporation of remote sensing data into public-health and risk management practices requires measurements that are at spatial and temporal resolutions appropriate to scale of the problems. In many cases, this means that data are needed at more finely detailed spatial and temporal resolutions than current technology allows. When rapid response to events is required, or where continuous monitoring can be used to identify anomalous environmental conditions, fine temporal resolution is required. Additionally, accuracy of measurements can be improved through aggregation of multiple observations over time; frequent observations can be used for these purposes as well. Experience with risk management applications (e.g., harmful algal bloom warnings and famine early warnings systems) suggests that fine spatial resolutions are required to target forecasts and warnings to specific geographical locations; such targeted warnings have been shown to be more effective than blanket warnings over entire regions, as discussed latter in this chapter.

The Importance of Moving Towards Operational Systems

To realize the potential benefits for improving human health by undertaking actions that result from the collection of remote sensing data, the panel recognizes the importance of moving space-based observation efforts from research to operations. Making the data collection operational, in the service of improving human health and security, requires that data be employed to address the five sets of activities listed above, and that information products be delivered to public health practitioners, risk managers, emergency responders, and the public in a timely and accurate manner. Additionally, the data need to be analyzed so that they are understandable in terms of the problems faced by decision makers, and at the scale of human decision making. The data need to be reliably available so that they can be evaluated sufficiently to the point that they are trusted by the public-health community and other users and so they can be relied upon as tools for making measurements that can serve as the basis for decisions that have life and death consequences. The panel recommends that emphasis be placed on three key investment priority areas that will improve the benefits of remote sensing for this purpose, in addition to the development of new sensing systems.

- First, continuity of systems that currently provide data to health-related programs and research is important. The existing base of users of space-based observations within the health community has experience with sensor systems like Landsat, AVHRR, and MODIS, and the continued availability of these data products will ensure that these users have access to data they understand (See Box 6.1). Also, research and applications in public health often require data in long time series to

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[1] For example, NASA's SEDAC, the socio-economic data and applications center, and its activities, such as the development of the Gridded Population of the World (GPW), the Human Footprint Dataset and the Global Distribution of Poverty, provide examples of effective translation of Earth observation data.

evaluate or predict how environmental changes against some baseline affect health. Sensor systems with a long-term archive of observations are most useful in such cases.

- Second, when new sensing systems are brought on line, investments are needed in training the public-health community, risk mangers, and emergency responders to make best possible use of these new sensors.
- Third, investments are also needed in research that develops decision-making frameworks, in tools that analyze space-based observations, and in tests of efficacy in the context of real-world health interventions.

BOX 6.1. LESSONS FROM LANDSAT

The history of the Landsat program provides useful lessons on how long-term data continuity and user training impact the application of satellite data to real-world problems. As the Landsat technology evolved from the late 1970s to the late 1980s, its scientific literature and its user community grew in size and expertise. By the mid-1990s it had a very large base of knowledgeable users and it formed a central theme of much remote sensing teaching at universities. Despite later setbacks (privatization in the late 1980s, the loss of Landsat 6 on launch, scan line corrector problems on Landsat 7), it continued its dominance into the new century, including an increase in interdisciplinary applications such a health, demographics, geology, etc.

As of this writing however, the Landsat era is threatened. With only Landsat 5 still operating properly, and no replacement ready in the near future, Landsat dominance in high resolution environmental monitoring may be over. University training programs are redoing their teaching materials to focus on new sensors. Change detection research programs are experiencing difficulties as new sensors are not backwards compatible with Landsat. Interdisciplinary research scientists now find that their hard-won expertise in Landsat data analysis is obsolete. They must seek out new collaborators with expertise in new systems.

Status of Existing/Planned Products and Needed Improvements

Many, but not all, of the desired satellite sensors relevant to human health and security already exist. However, because the sensors are beginning to fail, plans should be devised at a minimum for maintaining these sensors (or their equivalents) so that long-term, time-series research linking environmental processes to health risks or disease patterns can be continued. In addition, these time-series data maintained into the future will be critical to early warning of times and places where risk mitigation efforts are warranted. As has been pointed out in many other parts of this report, existing sensors are becoming non-functional, and replacement of equivalent or enhanced satellites and sensors is in some cases highly uncertain. The need for continued availability of the kinds of atmospheric and surface environmental data that have proven so informative to understanding health linkages can not be overstated. New sensors are being recommended, some that will gather similar data at a higher spectral resolution, or over a different horizontal span or time frequency.

PRIORITY NEEDS: OBSERVATIONS, MEASUREMENTS, AND TECHNOLOGY DEVELOPMENT

In the following section, we identify various needs that will help address human health problems in six areas of application:

- Ultraviolet radiation and cancer
- Heat stress and drought
- Acute toxic pollution releases
- Air pollution and respiratory/cardiovascular disease
- Algal blooms and water-borne infectious diseases
- Vector borne and zoonotic disease

These are linked to the missions that are discussed in detail elsewhere in this report. The rationale and means for application to societal benefits are outlined in each of these health domains.

TABLE 6.1 Human Health and Security Panel Priorities (Unranked) and Associated Missions

Brief Description of Mission	**Variables**	**Type of Sensor(s)**	**Coverage**	**Spatial Resolution**	**Frequency**	**Synergies with other panels**	**Related Planned or Integrated Missions (if any)**
Ozone Processes: Surface UV linked with Radiation/ Cancer	Stratospheric Ozone; Water vapor; Short-lived reactive species (OH, HO_2, NO_2, ClO, BrO, IO, $HONO_2$, HCl, and CH_2O); Isotope observations (HDO, $H_2{}^{18}O$, H_2O); Benchmark tracer data (O_3, CO_2, CO, HDO/H_2O, NO_y, N_2O, CH_4, halogen source molecules); Spectrally resolved radiance; Cloud and aerosol particles	Spectrally resolved radiometer (200-2,000 cm^{-1})	Global	5 km horizontal; 2-3 km vertical	TBD	Climate Ecosystems Weather	GACM ACE ASCENDS CLARREO GEO-CAPE GPSRO
Heat Stress & Drought	Rainfall; Soil moisture; Vegetation state; Temperature	Microwave sensors, Radar, Hyperspectral, Imagers	Global	1 km	Twice daily	Ecosystems Weather Climate	DESDynI GEO-CAPE HyspIRI LIST PATH SMAP GPM LDCM NPP/ NPOESS
Acute Toxic Pollution Releases	Visible atmospheric or hydrospheric plumes; Ocean color; Particle size; Gross vertical structure	High resolution imager (multispectral: UV-NIR)	Geostationary for Western Hemisphere	1 km (aerosols, ocean state, surface layers) 1-20 m (multi-spectral, high res) 30-50 m (high res, particles)	Daily Multi-day 15 min.	Ecosystems	GEO-CAPE ACE GACM GOES-R
Air Pollution: Lower troposphere linked with Respiratory and Cardio-vascular Diseases	Aerosol composition and size; NO_2, HCHO, VOCs, CO, SO_2; Tropospheric ozone	Multi-spectral UV/Vis/NIR/ TIR, LIDAR	Regional & Global	10 km horizontal; Boundary layer sensitivity 1 km; with vertical structure	Hourly (regional) ~ Days (global)	Climate	GACM ACE GEO-CAPE Glory
Algal Blooms and Water-Borne Infectious Diseases	Coastal ocean color; Sea-surface temperature; Atmospheric correction; Coastal ocean phytoplankton; River plumes	Multispectral	Regional	1 km 100 m	Daily Weekly	Ecosystems Water	SWOT ACE GEO-CAPE PATH SMAP LDCM NPP/ NPOESS
Vector Borne and Zoonotic Disease	Meteorological conditions (surface temperature, precipitation, wind speed); Soil moisture; Landcover status; Vegetation state	Hyperspectral; High resolution multi-spectral, RADAR, LIDAR		10s of meters 1 km (surface temp, soil moisture, veg. state)	> monthly Twice daily	Ecosystems Weather Water	SMAP DESDynI HyspIRI LIST PATH SWOT LDCM

Ultraviolet Radiation and Cancer

Mission Summary – Ozone Processes: Ultraviolet Radiation & Cancer	
Variables	Stratospheric Ozone; Water vapor; Short-lived reactive species (OH, HO_2, NO_2, ClO, BrO, IO, $HONO_2$, HCl, and CH_2O); Isotope observations (HDO, $H_2^{18}O$, H_2O); Benchmark tracer data (O_3, CO_2, CO, HDO/H_2O, NO_y, N_2O, CH_4, halogen source molecules); Spectrally resolved radiance; Cloud and aerosol particles
Sensor(s)	Spectrally resolved radiometer (200-2,000 cm^{-1})
Orbit/Coverage	LEO, global
Panel Synergies	Climate, Ecosystems, Weather

Background and Importance

The need to forecast ultraviolet (UV) dosage levels at the Earth's surface is a first order public health issue, as skin cancer is both a high frequency occurrence and a form of cancer with an increasing rate of occurrence despite the efforts of medical research. The American Cancer Society (2006b) estimates that, in 2006, more than 1,000,000 new cases of basal and squamous cell cancers would be diagnosed. In addition, 60,000 cases of melanoma, the most serious form of skin cancer, are diagnosed each year.

The catalytic destruction of ozone, that has been observed to occur predominantly in the lower stratosphere at high- and mid-latitudes over highly populated regions, is extremely sensitive to temperature through the potential catalytic conversion of inorganic halogens to free radical form on cold aerosols and ice particles. Recognition of that sensitivity has created a strong mechanistic link between the forcing of climate by increases in CO_2 and H_2O that radiatively cool the lower stratosphere, and studies of the loss of ozone by free radical catalysis. The strong links between skin cancer incidence, ozone loss by catalytic destruction in the stratosphere, and the response of the climate system to CO_2 forcing has joined these research communities in the pursuit of global UV dosage forecasts.

Role of Remotely Sensed Data

We considered the problem of understanding and forecasting human health effects from UV dosage levels in three parts. First, we address the mechanisms that control ozone catalytic destruction in the stratosphere (Figure 6.1). This region of the atmosphere is important because evidence gathered over the past thirty years has shown that this region has experienced the greatest loss. Second, we consider the impact that climate change will have on the processes that control ozone. Third, we briefly review what is known about the human response to increasing UV dosage.

Ozone is controlled in an important way by transport processes that move ozone poleward and downward from the same region at low latitudes. This large-scale transport is summarized in Figure 6.2, which shows convective injection of tropospheric air into the tropical lower stratosphere and into the midlatitude lowermost stratosphere (or "middle world"). Although this illustrates meridional transport, there are also very important longitudinal variations coupled to such large-scale events as monsoon structures and seasonal oscillation. The longitudinal variations tend to drive gyres that bring lower stratospheric air masses to amplify catalytic activity.

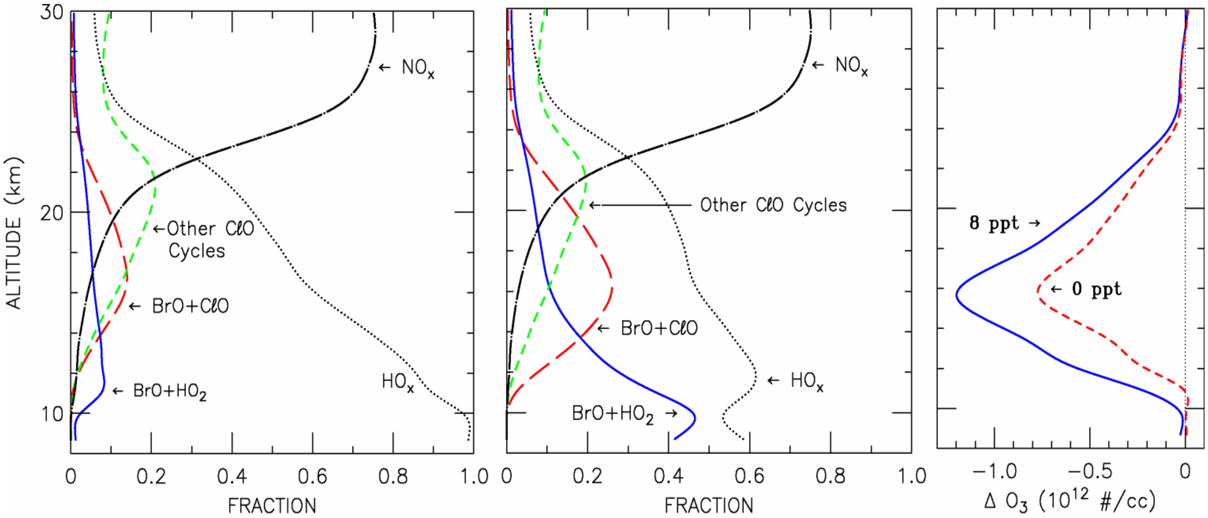


FIGURE 6.1 Ozone Photochemistry. Enhanced Bromine: Increased ozone depletion due mainly to BrO + ClO cycle. BrO + HO_2 cycle becomes a significant O_3 sink below 16 km (BrO + HO_2 does not drive O_3 depletion if Br_y^{Trop} is constant over time).

$Br_y^{Trop} = 0$ ppt $Br_y^{Trop} = 8$ ppt

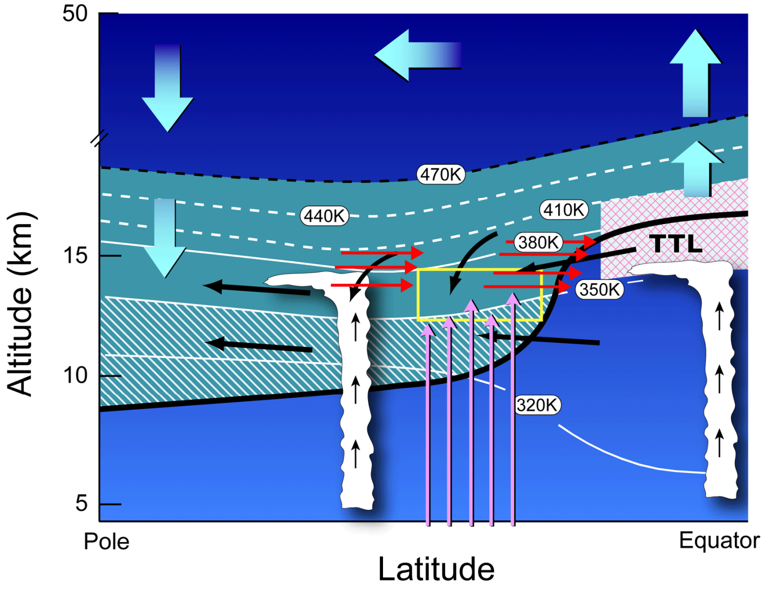


FIGURE 6.2 Convective injection of tropospheric air into various portions of the stratosphere

These observations of highly elevated water convected in the cold lower stratosphere raise the obvious potential for amplifying the destruction of ozone by catalytic loss. An example of those water vapor observations are shown in Figure 6.3.

The key concern that emerges from these observations is that the combination of lower temperatures and high water vapor concentrations can dramatically enhance the ClO concentration in particular. This effect is captured from Kirk-Davidoff *et al.* (1999) that plots the logarithmic increase in the reaction rate converting HCl and $ClONO_2$ to Cl_2 (and then to ClO) and $HONO_2$.)

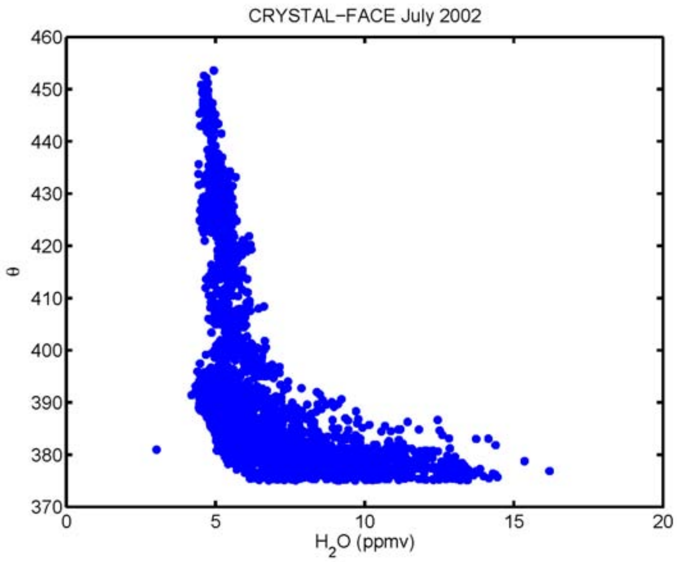


FIGURE 6.3 Observations of highly elevated water convected in the cold lower stratosphere.

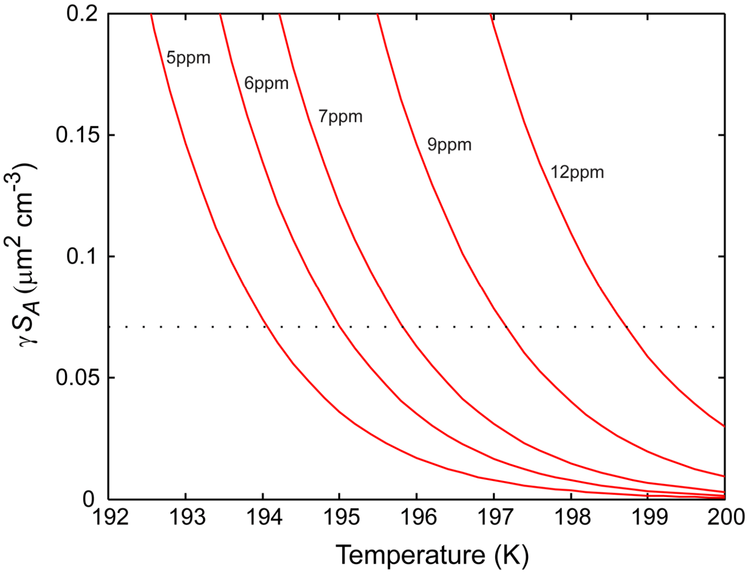


FIGURE 6.4 Logarithmic increase in the reaction rate converting HCl and $ClONO_2$ to Cl_2 (and then to ClO) and $HONO_2$ (From Kirk-Davidoff *et al.,*1999.)

While ClO is amplified by heterogeneous conversion of HCl and $ClONO_2$ to Cl_2 and $HONO_2$, the mechanism may well not be capable of sufficiently amplifying ozone loss (Smith et al., 2001). However, the link between the BrO and ClO cycles, rate limited by the reaction $ClO + BrO \rightarrow Cl + Br + O_2$ (McElroy et al., 1986) may provide an explanation. As Figure 6.1 reveals, small increases in BrO resulting from direct injection of short-lived organic bromines or BrO itself may well provide the solution to the puzzle of what has controlled changes in the ozone column concentration over the past two decades. Figure 6.5, from Salawitch et al. (2005) shows the impact of small additional amounts of BrO on the loss of ozone column resulting from the addition of aerosol precursors into the stratosphere by volcanic injection. Only with the addition of an additional 8 ppt of BrO can the large losses observed in the ozone column be quantitatively explained.

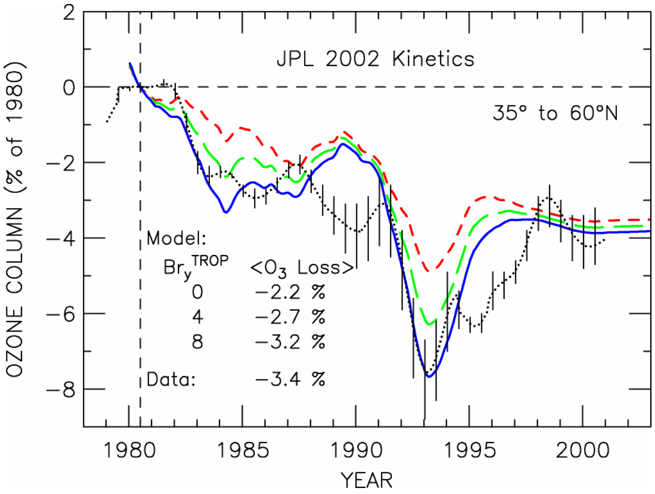


FIGURE 6.5 Impact of small additional amounts of BrO on the loss of ozone column resulting from the addition of aerosol precursors into the stratosphere by volcanic injection. From Salawitch et al*.,* 2005.

Recommendations

These observations provide the foundation of a strategy needed for the forecast of UV dosage at the Earth's surface over the next decades. The following objectives must be achieved:

- Catalytic destruction of ozone under conditions of low temperature and elevated water vapor by the combination of chlorine, bromine, and iodine must be defined by observing the ClO, BrO and IO concentrations in the lower stratosphere in the presence of elevated water vapor concentrations.
- Mechanisms controlling the dynamical coupling between the troposphere and stratosphere must be established using a combination of *in situ* isotopes, long-lived tracers, and reactive intermediates in order to establish how the irreversible flux of water vapor into the stratosphere will change given increased forcing of the climate system by CO_2, CH_4, etc.
- The role of convective injection of short-lived compounds through the tropical tropopause and by convection at midlatitude continental sites must be established.

These objectives require the following combination of high spatial resolution observations:

- The short-lived reactive species OH, HO_2, NO_2, ClO, BrO, IO, $HONO_2$, HCl, and CH_2O to pin down the chemical/catalytic/transport structure of the TTL and the injection of short-lived species into the overworld and middleworld from the troposphere
- Isotope observations of HDO, $H_2{}^{18}O$, H_2O obtained simultaneously in the condensed and vapor phase
- Benchmark Tracer data (O_3, CO_2, CO, HDO/H_2O, NO_y, N_2O, CH_4, halogen source molecules) to quantify the extent of horizontal mixing and entrained ambient air and to establish the spatial pattern of the age of the air
- Benchmark water vapor and total water: Instruments capable of measuring water vapor mixing ratios accurately and precisely outside as well as inside clouds. Uncertainties in relative humidity measurements are directly proportional to uncertainties in water

- Absolute, spectrally resolved radiance—upwelling and downwelling—throughout the thermal infrared (200–2,000 cm^{-1}), with a spectral resolution of ~ 1 cm^{-1} and an accuracy (absolute) of 0.1 K in brightness temperature
- Particle composition and number density: Instruments capable of determining in a single-particle and/or ensemble mode the chemical composition (preferably in a quantitative/stoichiometric way) of cloud particle and interstitial aerosol

A crucial aspect related to the forecasting of UV dosage over the coming decades is the determination of the impact on human morbidity and human mortality of these increased levels of UV. Given that skin cancer has continued to grow in incidence despite improving medical knowledge, a bridge must be built that encourages the atmospheric science community to interact more effectively with the public health community to more accurately evaluate human response to UV dosage levels. This is a recommendation of the human health panel over the next decade. The primary scientific questions that are directly linked to societal objectives include evaluating:

- Which mechanisms are responsible for the continuing erosion of ozone over mid latitudes of the Northern Hemisphere?
- Will rapid loss of ozone over the Arctic in late winter worsen? Are these large losses coupled to mid latitudes?
- How will the catalytic loss of ozone respond to changes in boundary conditions on water and temperature forced by increasing CO_2, CH_4, etc.?

Heat Stress and Drought

Mission Summary – Heat Stress and Drought	
Variables	Rainfall; Soil moisture; Vegetation state; Temperature
Sensor(s)	Microwave sensors, Radar, Hyperspectral, Imagers
Orbit/Coverage	Multiple, global
Panel Synergies	Ecosystems, Weather, Climate

Background and Importance

Current global warming scenarios indicate an increasingly frequent occurrence of regional droughts and heat waves over the next several decades (IPCC, 2001). These events have a significant effect on human health, agriculture and the natural environment. They often require an emergency health response, similar to a disease outbreak. An important component of society's preparation for a warming climate is improved prediction, monitoring, response and post-event analysis of these extreme events. Satellite sensing of temperature, moisture and vegetation will play a key role in this work, especially in "downscaling" the spatial analysis of heat and drought to the "human scale" of a few kilometers. Recent research has demonstrated the utility of remote sensing data for regional heat/drought analysis and put us in a good position to suggest future satellite-based monitoring and research strategies.

For purposes of this discussion, we define a drought as an extended period of time of low precipitation and/or high evapo-transpiration impacting natural vegetation and agriculture. A heat wave is an extended period of time during which the air or ground temperature is high (e.g., above 32°C /90°F in temperate regions) and well above the seasonal average. These two types of events are often coincident, as both are associated with warm winds, clear skies, increased evapotranspiration rates and a shift in the nature of the heat budget of the earth's surface. As soil moisture becomes depleted, the fraction of the sun's irradiance that is balanced by evaporative cooling diminishes. A greater fraction of the sun's heat goes into heating the lower atmosphere.

The physical effect of drought and heat on agriculture may be rapid or slow, but its human impact is often delayed until harvest time (see Table 6.2). The direct impact of a heat wave on human physiology is much quicker. Heat stress induced illnesses and deaths may begin to climb within just a few days after the start of extreme conditions. The sensitivity of humans to heat stress varies with genetics, age, and type of shelter, but large segments of society are susceptible to extreme combinations of heat and humidity. Typically, heat stress problems mount rapidly as the dewpoint climbs above 25°C /77°F). The ability of the human body to thermo-regulate is compromised beyond dew points of 30°C. High dew points slow the evaporation of moisture that the body uses to cool the skin. In affluent areas, these effects can be mitigated by air conditioning. The analyses of risk can be enhanced if they combine spatially explicit observations of potential heat stress with spatial data on at-risk populations.

TABLE 6.2 Some recent heat waves and droughts

Event	Year	Location	Impact
Heat wave	1987	Athens	~900 deaths
Heat wave	1995	Chicago	~700 deaths
Drought and heat wave	2002	Australia	Poor crop yields
Drought	2002	SW USA	Poor crop yield
Heat wave and drought	2003	France	~15,000 deaths and poor crop yield
Drought	2005	Illinois	Poor crop yield

Role of Remotely Sensed Data

Many aspects of heat and drought can be monitored by conventional meteorological networks of surface and upper air stations. These networks vary greatly in their density and efficacy across the world, however, and are generally insufficient for accurate monitoring on scales less than 100 km. One issue is that the spatial pattern of a heat wave usually has a small-scale component driven by patterns of vegetation, terrain, water bodies and urban surfaces which are unresolved by conventional climatological methods. (See Box 6.2). The second issue is that conventional measurements do not monitor the state of the vegetation or soil moisture that may be responding or contributing to the heat and moisture anomaly. Neither soil moisture nor surface radiative temperature is routinely monitored.

To supplement conventional observations, space-based monitoring methods have made major strides over the last twenty years (Kogan, 1997). Using AVHRR and MODIS reflective bands, time series of NDVI were generated to evaluate the state of vegetation relative to other years. Surface albedo and its impact on local climate can also be determined. These same satellite sensor systems include thermal sensors that can measure the surface radiative temperature and emissivity; both day and night. The 1-km spatial resolution of these sensors far exceeds the spatial resolution of weather-station networks. Column integrated water vapor can also be inferred, giving qualitative indications of humidity conditions under clear-sky conditions.

BOX 6.2 EUROPE HEAT WAVE

The European heat wave during the summer of 2003 included small scale features that could only be resolved with satellite remote sensing. By August of that year, a coupled pattern of high temperature and vegetation loss was located over central France, controlled in part by terrain and land use factors. The anomalies in vegetation index and surface temperature derived from MODIS are shown in Figures 6.6 and 6.7. On a still smaller scale, ASTER images reveal that pastures and active agricultural fields have lost their vegetation and heated significantly, while forests and inactive fields have a small temperature anomaly (Figure 6.8).

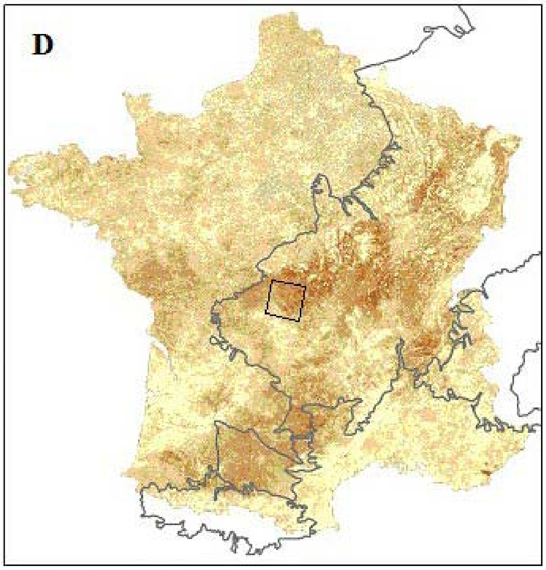


FIGURE 6.6 Vegetation index anomaly from MODIS in France for August 13-28, 2003, compared with the same dates in 2000-2002 and 2004. Yellow pixels are unchanged while brown pixels have decreased the index by 0.4. Solid lines demarcate conventional climate zones. (from Zaitchik et al., 2006).

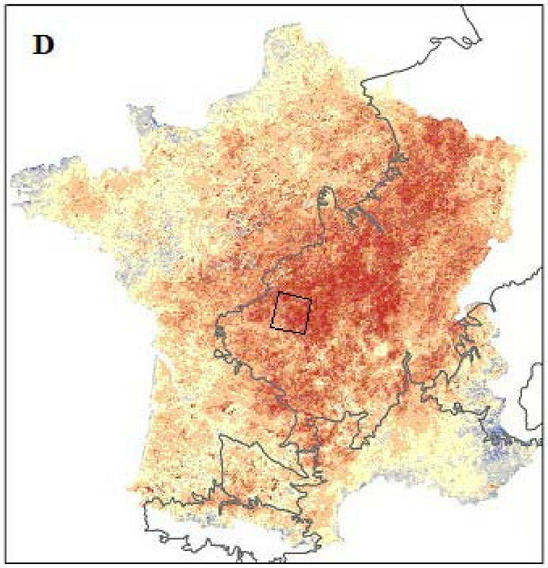


FIGURE 6.7 Similar to Figure 6.6 but for surface temperature anomaly. Gray areas are slightly cooler, yellow is unchanged and red is hotter by as much as 20ºC.

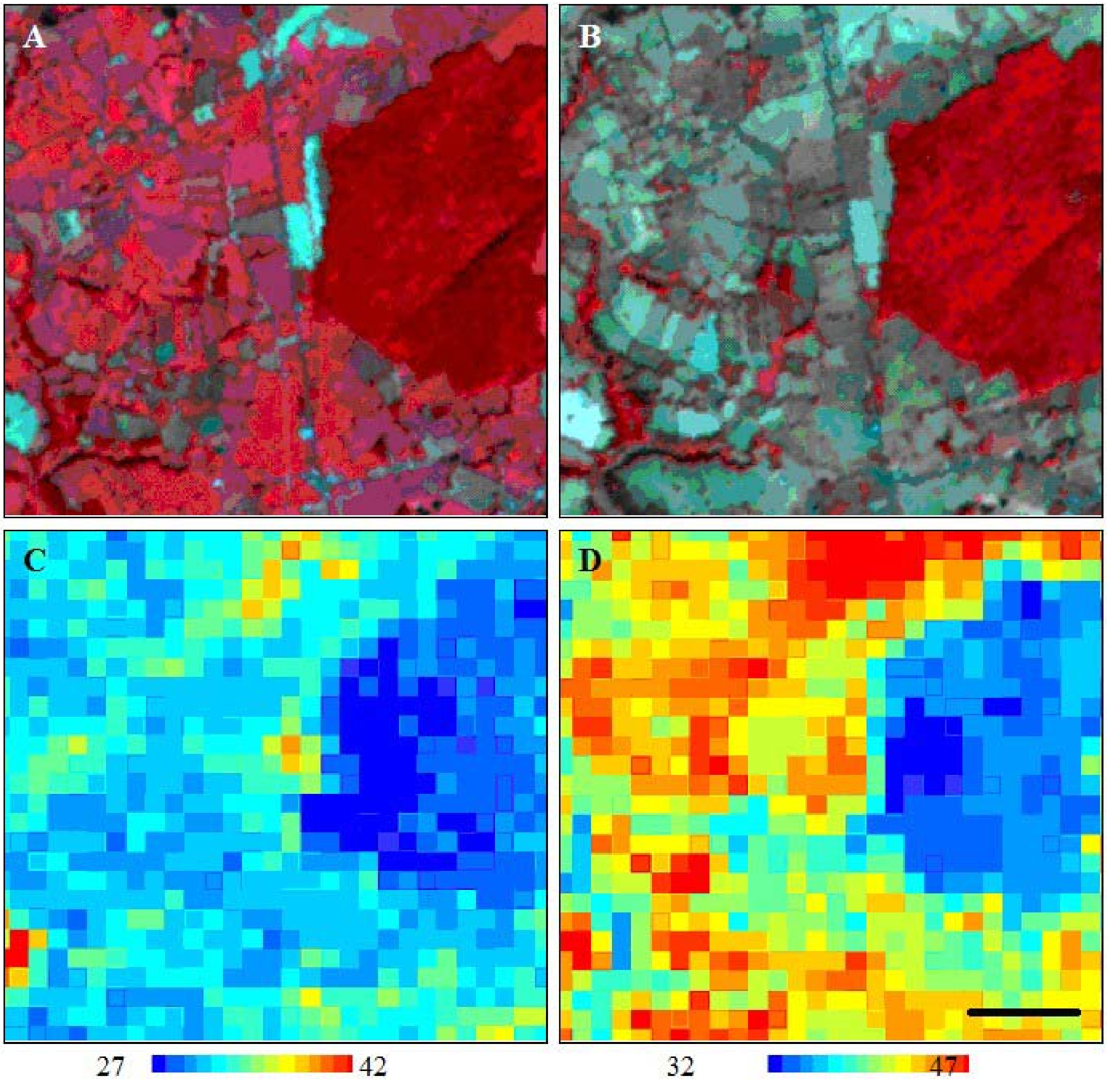


FIGURE 6.8 Small scale vegetation and temperature differences associated with the heat wave of 2003; seen from ASTER. Parts A and B are false color images for August 2000 and 2003, with vegetation in red and bare soil in pale blue. Parts C and D are the emission temperature for the same two dates (see color bar). The scale bar in the lower right has a length of 500 meters. The forest patch on the right stayed relatively cool while the impacted agricultural fields heated significantly. This scene location is part of the ASTER footprint shown in Figures 6.6 and 6.7.

A successful program for operational monitoring of drought conditions is the Famine Early Warning System run by USAID, NOAA and other agencies (http://www.fews.net/), and focused primarily on Africa. This system integrates satellite data (primarily AVHRR) with conventional climate data, meteorological models, and crop reports to issue regional Watch, Warning and Emergency drought notices (Buchanan-Smith, 1994; Herman et al, 1997). It is also used in the prediction of disease outbreaks that are environmentally triggered.

Finer scale aspects of heat waves have been studied using Landsat and ASTER (see Box 6.2). These satellites have much higher spatial resolution in both their reflective and thermal channels. They allow surface vegetation and temperature to be mapped down to the scale of cities, towns, agricultural fields and forest patches (i.e. 1 km), revealing important relationships between heat and land use. The urban "heat island" and the cooling effects of forests have also been mapped in this way (Lo et al. 1997). Unfortunately, these satellite/sensor systems have poor return times, typically 18 days or more, limiting their usefulness for monitoring.

Satellite-derived land-cover patterns are increasingly used as inputs to high resolution physical models of regional climates. In this way, satellites help in prediction, down-scaling, model verification and real-time monitoring of heat waves.

Future Needs

To maintain and enhance the ability to monitor heat waves and drought from space, we recommend the following future efforts. Needs for new sensor capabilities include:

- Develop new high-resolution satellite observations of rainfall and soil moisture, extend TRMM to high latitudes and advance microwave sensors such as SMOS (2007 launch) and HYDROS (2009 launch planned, but unlikely) – see recommendation presented in Chapter 7.

In order to enhance the operational capabilities and use of the sensor data, the panel recommends the following actions:

- Develop new strategies for increasing the return time of high resolution sensors
- Maintain the growth and use of the MODIS and ASTER archives
- Continue development and operationalization of the VIIRS sensor for long-term monitoring of MODIS-type information
- Implement an effective Landsat-7 follow-on program including a slightly enhanced reflective channel selection and an effective thermal band selection (Based on recent experience with the ATLSS (airborne), ASTER and Hyperion sensors)

Finally, the availability and use of remote sensing for drought and heat wave mitigation would benefit from additional support for research on heat waves and droughts that makes use satellite data from GOES, AVHRR, MODIS, Landsat, ASTER, and new sensors as well as *in situ* sensors.

Acute Toxic Pollution Releases

Mission Summary – Acute Toxic Pollution Releases	
Variables	Visible atmospheric or hydrospheric plumes; Ocean color; Particle size; Gross vertical structure
Sensor(s)	High resolution imager (multispectral: UV-NIR)
Orbit/Coverage	GEO, Regional
Panel Synergies	Ecosystems

Background and Importance

"Acute pollution events" are short-lived aperiodic events that discharge and disperse large amounts of anthropogenic or natural toxins or other hazardous substances into and through the environment. These events may be the result of natural phenomena such as wildfires, industrial accidents (freight train derailment, oil spill at sea, refinery fire), or terrorist acts that release radiological, biological or chemical agents into the air or water supply. The scales of these incidents can range from the microscale (tens of meters and tens of minutes) in some tanker truck chemical spills to the mesoscale (tens of kilometers and hours) for some refinery fires, to macroscale (months to years and hundreds to thousands of square kilometers) for red tide or volcanic eruptions. Similarly, the frequency of these events also varies widely, although detailed statistical summaries and analyses are lacking. EPA (2005) reports that the annual number of industrial accidents involving the release of hazardous substances from facilities required to have Risk Management Plans (RMPs) ranged from 225 to more than 500 over the nine-year period ending in 2003. The U.S. Coast Guard's National Response Center (www.nrc.uscg.mil/nrchp.html) reports spill incidents of all types in the U.S. numbered more than 35,000 in 2005. Between 1973 and 2001, the number of oil spills in and around U.S. waters (www.uscg.mil.hq/g-m/nmc/response/stats/aa.htm) has ranged from about 5000 in the late 1980s to a high of about 10,500 in 1978. Environment Canada (www.etc-cte.ec.gc.ca) reports there were 742 large oil tanker spills worldwide for the period 1974-1997, where "large" spills are those involving >1000 barrels (136 metric tons) of oil released per event in non-wartime incidents.

Concerning natural events, there has been an average of one red tide outbreak in Florida alone per year for the past three decades (see section on harmful algal blooms for discussion of the detection of harmful algal blooms and water borne pathogens by remote sensing). Apart from natural and accidental incidents, the potential for large-scale terrorist actions has received much attention and there is considerable research and planning aimed at thwarting these actions and minimizing their impacts. It is widely recognized that terrorist actions could involve spatial and temporal scales not dissimilar to those of the industrial accidents and natural phenomena cited above. Planning for possible terrorist actions has focused on the release of chemical, biological and radiological agents.

Although some chemical agents (see Box 6.3) may be observed from space (although not detected in the analytical sense), biological, radiological and most chemical agents will not be observable from space nor with imaging systems operated from aircraft. However, it is also likely that accompanying fires and explosions will release particulate matter or hydrometeors that will be visible from space.

BOX 6.3 TYPES AND PROPERTIES OF CHEMICAL AGENTS

Agents	Symbol	Boiling Point (°C)	Appearance
Nerve Agents			
Sarin	GB	158	clear/colorless
Soman	GD	198	clear/colorless
Tabun	GA	240	clear/colorless
GF	GF	239	N/A
VX	VX	298	clear, amber colored oil
Choking Agents			
Chlorine	Cl	-34	amber liquid, green vapor
Phosgene	CX	7.6	clear, colorless
Blood Agents			
Hydrogen cyanide	AC	25.7	colorless
Cyanogen chloride	CK	12.8	colorless
Blister Agents			
Distilled mustard	HD	215-217	clear/amber colored
Lewisite	L	197	dark/oily colored
Phosgene oxime	CX	53-54	clear, colorless crystalline/liquid

SOURCE: Adams (2002)

The recommendations presented here pertain to high-impact pollution events involving visible plumes with lateral scales ≥ several hundred meters and longitudinal scales ≥ several kilometers. Small-scale events such as tanker truck spills or explosions are not within the scope of these recommendations nor do these recommendations explicitly target very large-scale events such as large wildfires. The latter are already well documented by MODIS (http://maps.geog.umd.edu/) and other moderate-resolution imagers. Nonetheless, the high-resolution imagery recommended here would likely also be highly beneficial to wildfire responders and researchers. The recommendations presented here also reflect inputs from the National Atmospheric Release Advisory Center (Lundquist et al. 2006) at Lawrence Livermore National Laboratory and the NCAR Workshop on Air Quality Remote Sensing from Space: Defining an Optimum Observing Strategy, 21-23 February 2006 Edwards et al. 2006) .

Role of Remotely Sensed Data

A moderately high-resolution imaging capability in geostationary orbit can serve a multitude of emergency response applications: inland and coastal oil spills and algal blooms, industrial accidents, severe weather, and discharges of hazardous agents resulting from terrorist actions. Satellite imagery should be considered an important but partial solution to the emergency-response observation challenge; the total solution must involve an integrated approach that blends satellite observations with surface and airborne observations. Previous NRC reports have identified the Nation's needs related to the threat of terrorist activities. In particular, NRC (2003) recommended deployment of both permanent and rapid-response meteorological and plume monitoring systems.

The challenge then is to identify satellite-based systems that could provide imagery invaluable to the needs of emergency responders and health officials charged with managing and minimizing the impacts of natural and anthropogenic incidents where such incidents involve visible atmospheric or hydrospheric plumes. Both meteorological and plume observations are critical for analyzing and predicting atmospheric dispersion and deposition of gases and particles in an acute pollution event. The parameters needed include wind speed and direction, temperature, humidity, precipitation type and intensity, mixing height, turbulence, and energy fluxes. Table 6.3 summarizes the measurement requirements according to the associated dispersion and meteorological variables. The specific variables that must be measured may also be a function of the algorithms and parameterizations used in the dispersion model. Because of their height variability in the boundary layer, vertical profiles of many parameters are important. In the same way, spatial variability of the dispersion variables may necessitate multiple observing sites or spatial imagery. Table 6.4 expands on the applicability of high-resolution satellite imagery. It thus becomes clear that the ideal yet pragmatic solution is a geostationary imaging spectroradiometer in space having the following characteristics:

- Moderately high spatial resolution to capture plume horizontal structure
- Moderate view area to ensure that the visible plume can be observed in its entirety to quantify transport
- Pointing capability to ensure capturing scenes within the useful surface geometry viewed by the satellite
- Rapid refresh rate to map the temporal evolution of the plume and estimate the horizontal diffusivity (atmospheric and hydrospheric plumes have different requirements)
- Multiple channels to observe ocean color, estimate particle size, and estimate gross vertical structure (e.g. plume penetration of the inversion capping the surface-based mixed layer)

TABLE 6.3 Candidate meteorological and plume observing systems (adapted from Dabberdt et al., 2004).

Dispersion Variables	**Meteorological Variables**	**Candidate Measurement Systems**
Transport	Three-dimensional fields of wind speed and wind direction	Profilers; Doppler weather radar; RAOBs; mesonets; aircraft; tethersonde; Doppler lidar; satellite imagery
Diffusion	Turbulence; wind speed variance; wind direction variance; stability; lapse rate; mixing height; surface roughness	3D sonic anemometers; cup & vane anemometers; RAOBs; profilers; RASS; scanning microwave radiometer (maybe); tethersonde; satellite imagery
Stability	Temperature gradient; heat flux; cloud cover; insolation or net radiation;	Towers; ceilometers; profiler/RASS; RAOBs; aircraft; tethersonde; net radiometers; pyranometers; pyrgeometers; satellite imagery
Deposition, wet	Precipitation rate; phase; size distribution	Weather radar (polarimetric); cloud radar; profilers; satellite imagery
Deposition, dry	Turbulence; surface roughness	See ”Diffusion” above
Plume rise	Wind speed; temperature profile; mixing height; stability	Profilers/RASS; RAOBs; lidar; ceilometer; tethersonde; aircraft; satellite imagery

NOTE: RAOB – rawinsonde observation; RASS – radio acoustic sounding system

TABLE 6.4Applicability of satellite imagery to plume mapping and characterization for emergency response to large singular events

Plume Attribute/Feature	Priority	Feasibility	Comments
Vertical resolution	3	3	Terrestrial observations likely to be more effective
Vertical extent	2	2	Does the plume penetrate into the free troposphere?
Horizontal resolution	1	1	Co-paramount with “coverage”
Horizontal extent/coverage	1	1	Plume transport direction is the most important parameter
Temporal resolution/refresh rate	1	1	High temporal resolution is important for diffusion, and moderate temporal resolution is valuable for transport
Particle sizing	4	3	Terrestrial observations likely to be more effective
Species identification	5	3	Terrestrial observations more effective
Diurnal observations	1	1	Important, while recognizing that nocturnal observations will have reduced resolution

NOTE: 1 = highest priority/greatest feasibility; 3 = least feasibility; 5 = lowest priority.

Figures 6.9 and 6.10 illustrate imagery of three different large acute pollution events as taken from three different satellites. The particle plume from the collapse of the World Trade Center on September 11, 2001, is seen in Figure 6.9 from a 20-m resolution image taken by the French SPOT polar orbiting satellite. About three kilometers downwind from the WTC, the visible plume is about one kilometer wide. The 20-m resolution is able to depict much of the turbulent structure of the plume. Figure 6.10 is an image of the 21 February 2003 oil terminal fire on Staten Island, New York, as observed by SeaWiFS, a sun-synchronous orbiting satellite with 24 hour revisit time and 1.13 km resolution at nadir. The figure illustrates the vastly improved quantitative information obtained from the high-resolution SPOT imagery in comparison with nominal 1-km imagery of GOES and SeaWiFS. The images also suggest that “moderately high-resolution” – say, around 50m – is a reasonable compromise considering cost and the monitoring demands imposed by large-impact events, such as refinery and chemical plant fires. A precise specification for horizontal resolution remains to be developed.

FIGURE 6.10 SeaWiFS image of the visible plume from the Staten Island oil terminal fire (arrow points to fire site). This true-color image of the U.S. northeastern coastline was acquired on February 21, 2003, by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) several hours after the explosion. The dark smoke can be seen clearly in contrast with the whiter clouds in the area and the snow-covered landscape. In this scene, the smoke plume stretches about 150 kilometers (93 miles) to the ESE of the fire. SOURCE: Courtesy the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE.

FIGURE 6.9 SPOT multi-spectral image with 20 m resolution taken 87 minutes after the collapse of the North Tower of the World Trade Center (WTC) and 110 minutes after the collapse of the WTC South Tower, clearly showing the particle plume transport to the SE. Approximately 3 km from the source, the visible plume is about 1 km wide. (SPOT image © CNES/SPOT 2001)

Recommendations

A special events imager instrument in geostationary orbit would be invaluable for observing the time evolution of coastal and ocean pollution sources, tidal effects, and high frequency eddy currents, origin and evolution of aerosol plumes, and observations of tropospheric ozone. The imager requires a wide range of wavelengths (18 channels from UV to near-IR), spatial resolution of about 50 meters, and high temporal resolution (less than 1 minute per image). The frequent observations will reveal currently hidden processes and relationships in the Earth's oceans, on land surfaces, and in the atmosphere. This type of time-resolved data is currently not available from any satellite observations.

Such a special events imager would meet all of the requirements for observing the "*very large*" acute events, including wildfires and very large refinery fires, and the harmful algal blooms discussed later in this chapter. The imager would also meet the more demanding requirements needed to support emergency response dispersion modeling of the more common *large* acute events associated with train accidents, chemical upsets, oil spills, terrorist actions and the like. Recent discussions with the Co-Investigator responsible for the design of an imager with more limited spatial resolution (Herman, 2006) indicate that achieving the more rigorous requirements for a special events imager are feasible with today's technologies..

It may also be possible to achieve the higher resolution with a post-processing technique called "super resolution," or through a combination of improved optics and post processing. Super-resolution imaging (see summaries by Borman and Stevenson, 1998; Park et al., 2003; Vandewalle et al., 2006) constructs a high resolution image from a set of low resolution images that are taken from almost the same point of view. This enables super-resolution techniques to reconstruct an image with a spatial resolution greater than the typical diffraction limit of the telescope. Figure 6.11 illustrates the technique as applied by Emery (2003) to 1 km AVHRR images of the Death Valley region. In this reconstruction subsequent AVHRR passes sample the scene from slightly different locations. This can also be done in real time from geostationary orbit by over-sampling in the image backplane and reconstructing the enhanced image.

The Health and Security Panel recommends that NASA assign priority to the development and launch of a special events imager mission to provide the capability needed by federal, state and local emergency managers to best respond to a plethora of natural, accidental and overt environment emergencies. The mission is feasible and would provide a valuable service to the nation.

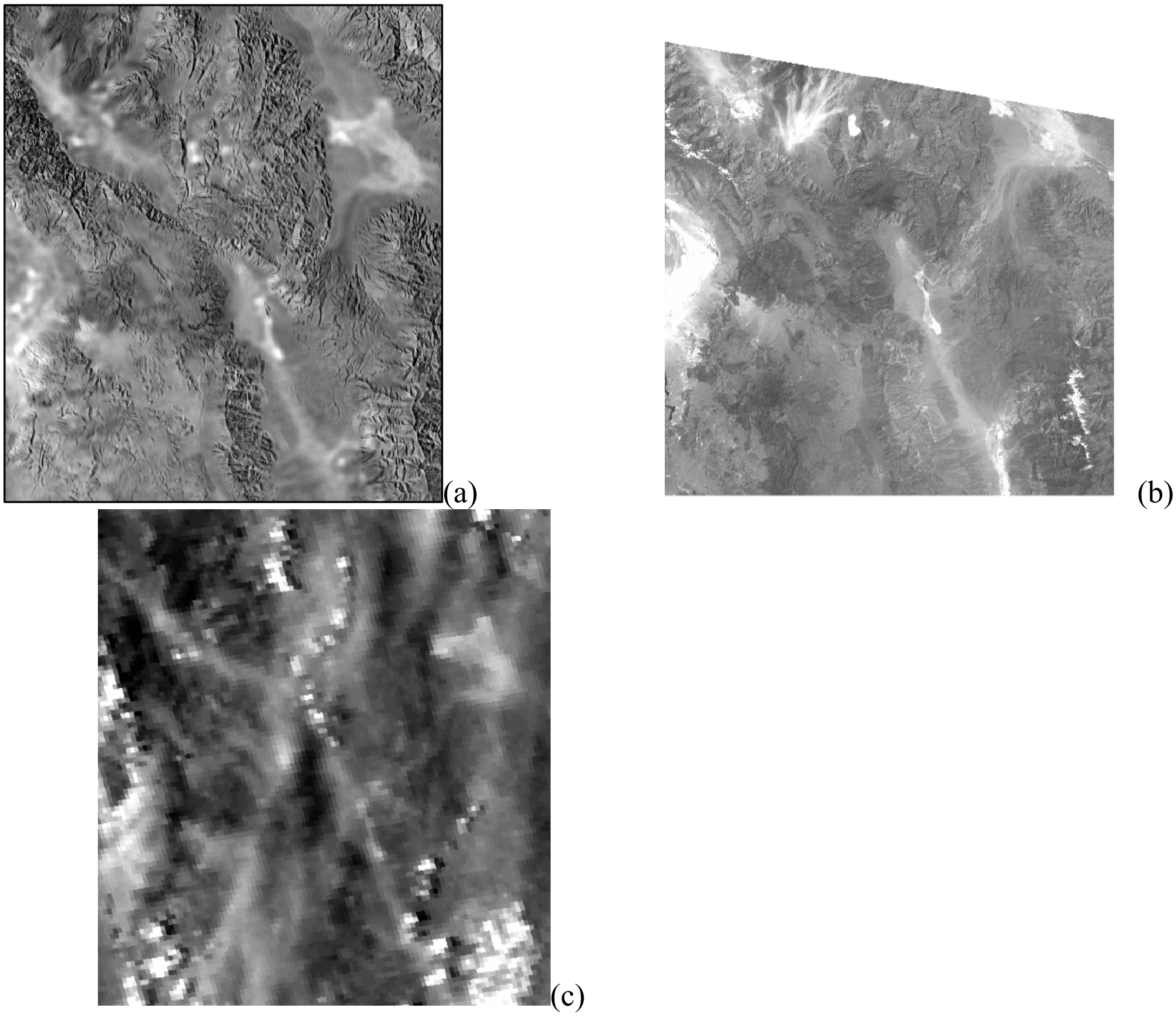


FIGURE 6.11 Comparison of enhanced-resolution AVHRR image with a high-resolution Landsat MSS Image (centered at 36.5° N, 117.5° W); courtesy of Emery (2003). (a) Super-resolution reconstruction, (b) Landsat MMS Channel 1image sampled (c) Original AVHRR 1-km image (180m res.) of AVHRR 1 km near-IR image to 180 m resolution (April 25, 1992) sampled at 180m (22:27GMT, May 7, 1992).

Air Pollution and Respiratory/Cardiovascular Diseases

Mission Summary – Air Pollution: Respiratory/Cardiovascular Diseases	
Variables	Aerosol composition and size; NO_2, HCHO, VOCs, CO, SO_2; Tropospheric ozone
Sensor(s)	Multi-spectral UV/Vis/NIR/TIR, Lidar
Orbit/Coverage	LEO & GEO, regional & global
Panel Synergies	Climate

Background and Importance

Air pollution, particularly in the lower troposphere, is a major cause of cardiovascular and respiratory disease (EPA, 2004, 2006). The main harmful pollutants are ozone and fine particles (aerosols), produced by chemical reactions involving nitrogen oxides ($NO_x = NO + NO_2$), volatile organic compounds (VOCs), carbon monoxide (CO), and sulfur dioxide (SO_2). Table 6.5 lists air quality standards in the United States and Europe. The United Sates has an 8-h standard for ozone, and 1-day and 1-year standards for airborne particulate matter (also referred to as aerosols). By these standards, one-third of the U.S. population is breathing unhealthful air (EPA, 2003). Europe has much tighter ozone standards (that are routinely exceeded). Air quality in China, India, and other rapidly industrializing nations is worse than in the United States or Europe.

Role of Remotely Sensed Data

Recent advances in tropospheric remote sensing have revealed the potential for applying satellite observations to air quality issues. Observations of NO_2 and formaldehyde from GOME, SCIAMACHY, and OMI have been used to place top-down constraints on sources of NO_x and VOCs. Observations of CO from MOPITT and AIRS have been used to constrain CO sources and to track the intercontinental transport of pollution. Combined observations of ozone and CO from TES and MLS have mapped the continental outflow of ozone pollution. Aerosol optical depth (AOD) observations from MODIS and MISR have been used to infer surface air concentrations of aerosols. Assimilation of MODIS AOD observations and OMI ozone is being implemented in air quality analyses and forecasts.

TABLE 6.5. Ozone and aerosol air quality standards in the U.S. and Europe

Pollutant of Concern	**Ambient Air Quality Standard**	
	United States	**European Union**
Ozone	84 ppbv (8 hour average)	55 ppbv (8 hour average) AOT40 (seasonal total)[a]
PM2.5[b]	15 μg m^{-3} (annual) 65 μg m^{-3} (24 hour average)	--[c]
PM102	50 μg m^{-3} (annual) 150 μg m^{-3} (24 hour average)	40 μg m^{-3} (annual) 50 μg m^{-3} (24 hour average)

[a] No more than 5000 ppbv-hours in excess of 40 ppbv during daytime hours in April-September. This corresponds roughly to a 43 ppbv daytime average.

[b] Particulate matter less than 2.5 μm radius (PM2.5) or 10 μm radius (PM10)

[c] See proposal for a European Union Directive on Clean Air for Europe with respect to particulate matter exposures europa.eu.int/comm/environment/air/cafe/pdf/cafe_dir_en.pdf

Mercury is a neurotoxin and a major public health concern. It is transported on a global scale in the atmosphere, depositing and accumulating far from its sources. Sources from combustion have been declining in North America and Europe due to regulation but have been rising rapidly in Asia, so that the global mercury pool in the environment continues to increase. Attempts at international agreements have been thwarted on a scientific level by poor understanding of the atmospheric redox Hg(0)/Hg(II) chemistry, which determines mercury deposition as Hg(II), and by the role of re-emission from surface reservoirs. Improved and expanded atmospheric observations are critically needed to expand our knowledge base through the testing of models. Although mercury is not directly observable from space, an effective observational strategy should integrate *in situ* measurements from the surface and from aircraft with satellite observations of correlated species (e.g., CO from combustion). Also of considerable interest are LEO satellite observations of tropospheric BrO by solar backscatter, as Br atoms could represent a major global oxidant for Hg(0). Tropospheric BrO retrievals are available from OMI and its predecessors (GOME, SCIAMACHY) but have yet to be validated with aircraft observations. They suggest that elevated levels of BrO, known to occur acutely in Arctic spring and to be responsible for enhancing mercury deposition there, could in fact be found ubiquitously in the troposphere.
This represents an important case study for the effective combination of aircraft, satellite and modeling studies that are delineated in Figure 6.12. Particularly in the case of human health, the critical importance of innovative coupling between *in situ* and remote observations requires fundamental restructuring of the Earth sciences in service to society.

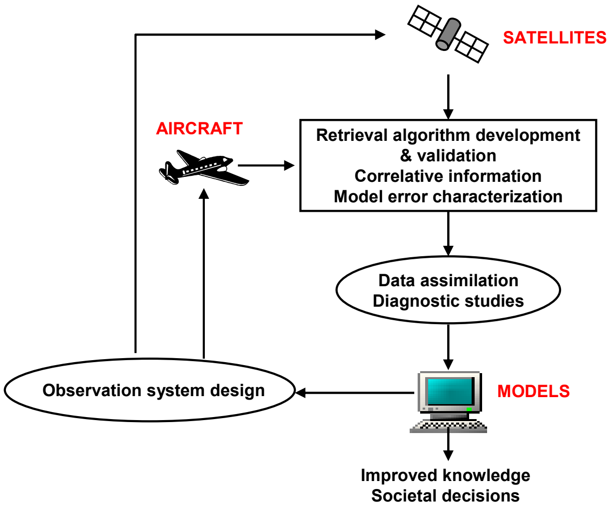


FIGURE 6.12 A key link between scientific development and the accomplishment of societal objectives is the effective integration of satellite, aircraft, and modeling studies. An important example for human health in the tracking and diagnosis of the chemistry linking mercury release and the reactions of halogen compounds that sequester heavy metals at high latitudes of the northern hemisphere.

However, the instruments presently in space have serious limitations for air quality applications (they were not, in general, designed for that purpose). Developing an improved capability for air quality observations from space was the focus of the recent Community Workshop on Air Quality Remote Sensing from Space (NCAR, 2006). The workshop identified future satellite observations as crucial for air quality management, involving four axes of application: (1) forecasting and monitoring of pollution episodes, (2) emissions of ozone and aerosol precursors, (3) long-range transport of pollutants extending from regional to global scales, and (4) large releases from short-duration environmental disasters. The need was strongly stated for a new generation of satellite missions as part of an integrated observing system including also surface air monitoring networks, *in situ* research campaigns, and 3-D chemical transport models.

Recommendations

Top-priority measurements from space for which capabilities have been demonstrated (but still need improvement) include tropospheric ozone, CO, NO_2, HCHO, SO_2, and aerosols. A high priority is to improve the ability to observe aerosol composition and size distribution from space.

Resolution requirements for air quality observations from space include a horizontal pixel size of 1-10 km with continental to global coverage, ability to observe the boundary layer, and a return time of a few hours or less. These requirements are defined by the need to observe (1) the development of pollution episodes, (2) the variation of emissions, and (3) the state of atmospheric composition for purposes of forecasting. Hourly resolution in polluted regions is highly desirable, as it matches the temporal resolutions of surface monitoring data and regional models, as well as the metrics used in air quality standards. Outside of these regions, temporal resolution can be relaxed to a few times per day for observation of long-range transport. For trace gases, multi-spectral methods combining UV/Vis, near-IR, and thermal IR can offer boundary layer information at least for ozone and CO. Active (lidar) observations can provide high vertical resolution for aerosols and ozone but with sparse horizontal coverage compared to passive techniques.

Meeting all the above requirements cannot be achieved from a single platform. Within the framework of existing or readily developable technology, the highest priority is for a GEO mission, with North America being of prime domestic interest. The satellite should have spectral observation capabilities ranging from the UV-A to the thermal IR. Two shortcomings of GEO are lack of global coverage and limited vertical resolution. These shortcomings should be overcome with a companion LEO platform including (1) a high spectral resolution lidar for vertical resolution of the boundary layer aerosol and free tropospheric plumes; (2) multi-spectral passive sensors ranging from the UV-A to the thermal IR for global observation of pollutant transport.

Algal Blooms and Water-Borne Infectious Diseases

Mission Summary – Algal Blooms and Water-borne Infectious Diseases	
Variables	Coastal ocean color; Sea-surface temperature; Atmospheric correction; Coastal ocean phytoplankton; River plumes
Sensor(s)	Multi-spectral
Orbit/Coverage	GEO, regional
Panel Synergies	Ecosystems, Water Cycle

Background and Importance

The rapid proliferation of toxic or nuisance algae, termed harmful algal blooms (HAB), can occur in marine, estuarine and freshwaters, and are one of the most scientifically complex and economically significant water issues facing the United States today. HAB toxins can cause human illness and death, halt the harvesting and sale of fish and shellfish, alter marine habitats, and adversely impact fish, endangered species, and other marine organisms. Previously, only a few regions of the United States were affected by HABs, but now virtually every coastal state reports major blooms (Harrness 2005) (Figure 6.12). Economic losses associated with HABs are expected to exceed $1 billion over the next several decades while a single HAB event can cause millions of dollars in damages in coastal economies through direct and indirect impacts (Anderson et. al. 2000).

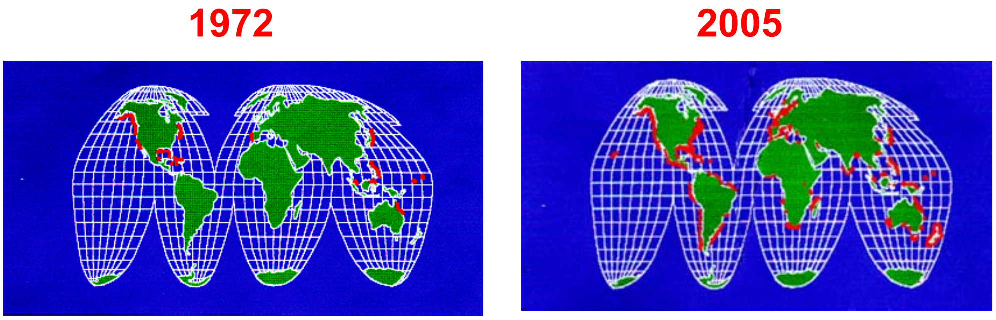


FIGURE 6.13 Harmful Algae: An Emerging Issue. Global distribution of harmful algae from the early 1970s to 2005. The red lines indicate areas where harmful algal blooms have been documented.

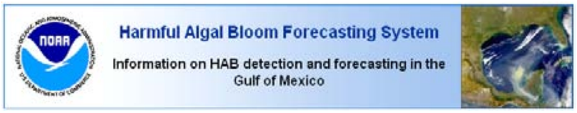
In addition to HABs, there are water-borne pathogens that cause human disease and are transmitted in drinking water, recreational exposure to contaminated water or via ingestion or inhalation (NRC 2004). More than 9 million cases of waterborne diseases are estimated to occur in the United States each year (Rose et al. 2001). Most water-borne pathogens are enteric and spread through fecal-oral pathways from animal and human fecal sources and introduced to waterways through sewage discharges, urban and agricultural runoff, and from vessel ballast. Some of the more severe waterborne diseases are hepatic, lymphatic, neurologic, and endocrinologic diseases and include *Vibrio cholerae* (Lobitz et al. 2000). To develop microbial risk assessment models for water-borne diseases, it is necessary to study the fate and transport of these pathogens, or the conditions that promote them, across the landscape via aquatic systems. Table 6.6 lists selected events demonstrating the use of remote sensing to detect and monitor harmful algal blooms (red tides) and waterborne pathogens

TABLE 6.6 Selected events demonstrating the use of remote sensing to detect and monitor harmful algal blooms (red tides) and waterborne pathogens.

Year	Event	Citation
1975-1986	5 Citations on remote sensing and red tides	
1975	First use of thermal imagery to identify ocean frontal zones where harmful algae were concentrated	Murphy et al. 1975. Limnology and Oceanography 20:481-486
1987-1996	28 Citation on remote sensing and red tides	
1987	First use of thermal imagery to track oceanic currents responsible for the transport of harmful algae	Tester et al. 1991. Limnology and Oceanography 36:1053-1061
1988-1990	NOAA's Coastwatch Program developed to provide timely access to near real-time satellite data for US coastal regions	http://coastwatch.noaa.gov/
1997-2006	76 Citations on remote sensing and red tides	
2000	Use *of remote sensing* for detection of *Vibrio cholerae* by indirect measurement	Lobitz et al. 2000
2001	Experimental harmful algal bloom forecast	Stumpf et al. 2003
2006	First operational forecast for harmful algal bloom	www.csc.noaa.gov/crs/habf/ (see Box 6.4)

SOURCE of citations Cambridge Abstracts – Aquatic Science.

BOX 6.4 RED TIDES



Harmful Algal Bloom Forecasting System

Information on HAB detection and forecasting in the Gulf of Mexico

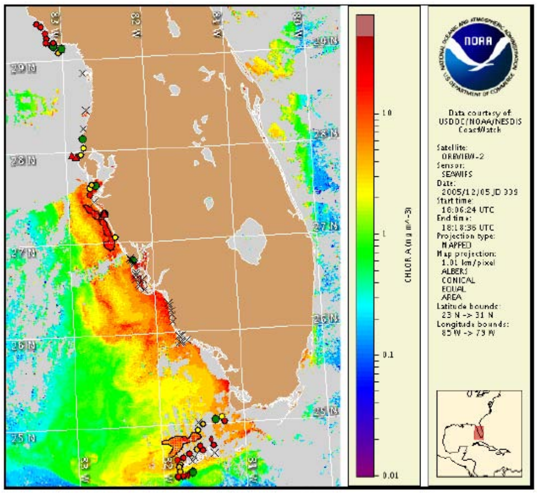
http://www.csc.noaa.gov/crs/habf

Blooms of the toxic dinoflagellate *Karenia brevis* are commonly known as red tides or harmful algal blooms. These blooms are responsible for serious public health problems and shellfish harvesting closures in the Gulf of Mexico every year. The National Oceanic and Atmospheric Administration (NOAA) provides the Harmful Algal Bloom (HAB) Bulletin to help coastal resource managers decide where to focus their sampling efforts and prepare for these blooms.

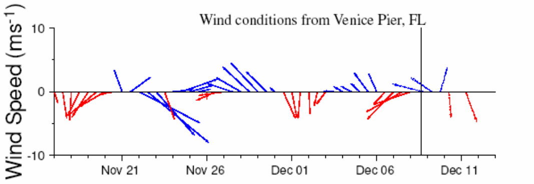
The HAB Bulletin uses satellite imagery, field observations, and buoy data to provide information on the location, extent, and potential for development or movement of *Karenia brevis* blooms in the Gulf of Mexico. When a bloom is present, the information is sent twice a week via e-mail to natural resource managers. Seventy-two hours after the bulletin has been issued, it is posted to the CoastWatch Harmful Algal Bloom Bulletin Web site for public access.

Each bulletin includes satellite image interpretation, analysis of past and forecasted wind data from NOAA's National Weather Service and National Data Buoy Center, and field data regarding *Karenia brevis* cell concentrations from the state of Florida.

Based on bloom concentration and prevailing winds, a conditions report is available to the public on the HAB Forecasting System Web site. The conditions report contains general information on bloom location and expected coastal impacts. This information was developed with state and local agencies, tourist boards, and citizen groups to provide accurate information to a non-technical audience.



Satellite chlorophyll image with possible HAB areas shown by red polygon(s). Cell concentration sampling data shown as red squares (high), red triangles (medium), red diamonds (low b), red circles (low a), orange circles (very low b), yellow circles (very low a), green circles (present), and black "X" (not present).



Wind speed and direction are averaged over 12 hours from buoy measurements. Length of line indicates speed; angle indicates direction. Red indicates that the wind direction favors upwelling near the coast. Values to the left of the dotted vertical line are measured values; values to the right are forecasts.

Role of Remotely Sensed Data

Chief among the needs to mitigate the effects of HABs and water-borne pathogens is the ability to detect, monitor, and forecast them in a cost effective and timely manner to protect human health. Ocean color and sea surface temperature satellite imagery are useful for detecting and tracking HABs (Stumpf and Tomlinson, 2005; Tang et al. 2003). In ocean color imagery algal blooms are detected based on the differential absorption and backscatter of irradiance; certain species are more amenable to detection because of reflectance characteristics of the cells (Carder et al. 1986). A new operational HAB forecast has been used in the Gulf of Mexico since 2004, providing twice weekly or daily forecasts, if conditions warrant, of bloom intensity and location (Stumpf 2001; Stumpf et al., 2003). Information is relayed via a bulletin (www.csc.noaa.gov/crs/habf/) to local managers who use this information to optimize sampling locations, focus resources and to notify the public of potential bloom conditions (Backer et al. 2003) (see Box 6.4).

Detection of phytoplankton blooms by remote sensing relies on the spectral quality, thermal signature and hydrographic features of the waters surrounding a bloom. Frequently blooms are found along frontal zones, and these hydrographic features may be coherent over scales of 10^2-10^3 km^2. The physical and biological factors affecting bloom dimensions are critical because resolution of patches < 5-10 km^2 is generally not possible with current technology. Major ocean current systems are frequently implicated in the transport of harmful algal blooms and indicative of conditions that support *Vibrio cholerae.* These currents can be tracked most simply and reliable using thermal AVHRR imagery (Lobitz et. al. 2000; Tester and Steidinger, 1997). The most common use of remote sensing to track the transport and dispersion of waterborne pathogens is by using storm water run off plumes as surrogates for direct detection. Thermal, ocean color, Landsat Thematic Mapper (TM) and synthetic aperture radar imagery have all successfully tracked storm water plumes (DiGiacomo et al. 2004, Nichol 1993) however, use of remote sensing imagery by public health programs is not yet widely practiced.

Recommendations

Expectations of public health officials and marine resource managers are that, in the coming decade, regional HAB forecasts will be available for all coastal areas in the United States. To accomplish this goal, additional sensors, missions and resources are needed. The GOES-R Coastal Water Imager (https://osd.goes.noaa.gov/coastal_waters.php) may be the most important advance for satellite detection of HABs in coastal and estuarine waters. The GOES-R platform offers frequent repeated views of an area to reduce the effects of cloud cover. Secondly, the coastal zone needs higher resolution than the 1 km produced by MODIS and the proposed ~0.7 km resolution of VIIRS (VIsible InfraRed Spectrometer) on NPOESS (Visible/Infrared Imager/Radiometer Suite) (see http://www.ipo.noaa.gov/Technology/viirs_summary.html). Typically, the first two pixels nearest the shore line are lost; this means that with VIIRS scenario the proposed resolution of GOES-R is ~ 0.3 km at the equator. This equates to between 0.4 to 0.45 km for most U.S. coastal waters.

Importantly, the detection of blooms along the coast, in turbid, pigment rich water requires more information than is available with SeaWiFS, MODIS, and the proposed VIIRS. Atmospheric correction is extremely difficult in coastal areas, and requires more bands than are currently planned. The set of ocean color instruments, SeaWiFS, MODIS, and VIIRS, were designed for open ocean work. As such, they have two NIR bands for atmospheric correction and most bands in the blue, where the open ocean ("blue water") changes color significantly. Along the coast, three NIR bands are needed for atmospheric correction. Red bands are needed to identify algae and separate it from turbidity and tannic acids. At least 10 bands are needed for an effective coastal sensor (three blue, two green, two red, and three NIR); a 12 band sensor would be optimal (three blue, three green, three red, three NIR).

In summary, more frequent imagery (GOES- R w/Coastal Sensor) with higher resolution and sensors with additional bands specifically for resolving chlorophyll signals in Case II (coastal) waters.

Vector Borne and Zoonotic Disease

Mission Summary – Vector Borne and Zoonotic Disease	
Variables	Meteorological conditions (surface temperature, precipitation, wind speed); Soil moisture; Landcover status; Vegetation state
Sensor(s)	Hyperspectral; High resolution multi-spectral, Radar, Lidar
Orbit/Coverage	Multiple, global
Panel Synergies	Ecosystems, Weather, Water Cycle

Background and Importance

Infectious diseases still account for more than 25% of deaths, globally. Remote sensing at moderate to coarse spatio-temporal resolution focused on the visible and near infra-red portion of the spectrum already has shown exceptional promise in applications to many aspects of public health, especially in risk assessment from infectious diseases caused by pathogens transmitted to people by arthropods (insects, ticks) or from non-human animals (mammal or bird reservoirs). We group these diverse and widespread infectious diseases into the broad category of vector-borne and zoonotic (VBZ) diseases.

VBZ diseases, such as malaria, dengue, and filariasis are believed responsible for millions of deaths and tens of millions of illnesses annually. The introduction and spread of West Nile virus through North America by mosquitoes during the past five years and recent concerns about the world-wide dissemination of H5N1 avian influenza are key recent examples where large human populations have come at risk over extensive geographic regions in short periods of time by these VBZ diseases. The recent appearance and spread of Chikungunya virus by mosquitoes among the islands of southeast Africa and the Indian Ocean demonstrates the explosive growth of vector-borne diseases under permissive environmental conditions (http://www.who.int/csr/don/2006_03_17/en/). During a one year period (March 2005-2006) it is estimated that 204,000 of La Reunion's population of 770,000 became ill from this mosquito-borne virus. Similar epidemics occurred during the same time in Mayotte, Seychelles and other islands throughout the region, with cases exported to at least five European countries by travelers. Even in the absence of high mortality, morbidity associated with explosive epidemics tax the health-care and economic infrastructures of affected regions. The suspicion of vector-borne disease outbreaks, itself, often engenders substantial economic losses, such as the report of bubonic plague around Surat, India in 1994. It was estimated to cost the government $600 million in lost revenues from exports, tourism, and job loss.

Attempts to control VBZ disease epidemics with limited available resources are hindered by the ability to prioritize and target areas for intervention. From a practical perspective, satellite observations offer an important opportunity to assess the likelihood of spatial diffusion of disease, and to monitor its timing and pattern. Identifying and validating the relationship between remote sensing data and health outcomes remains a major public health research focus. Space-based applications to VBZ diseases run the gamut from basic research questions identifying environmental risk signatures, to strategies for integrating remote sensing into operational decision support systems. The major goal of such efforts is to establish relationships between environmental conditions, as monitored by satellites, and risk to human populations from VBZ diseases. This goal requires improved characterization of the earth's land use, ecological changes and changing weather, at finer spatial and temporal scales.

Past Applications

Some of the earliest attempts to use remote sensing data extend to nearly 25 years ago, using satellite sensors to identify breeding sites of mosquito species responsible for VBZ diseases. For example, Linthicum et al (1990) used AVHRR data to locate increased breeding and subsequent Rift Valley Fever (RVF) virus activity in East African mosquitoes. RVF is both a human and agricultural risk. Washino and colleagues (1993) demonstrated that Landsat could identify agricultural sites that were most likely to produce mosquito vectors of malaria. The underlying rationale for remotely sensed data to examine VBZ disease patterns is that environment, landuse/land cover, weather, and human behavior underlie the distribution and spread of many of the most important infectious agents. Environmental structure and meteorological conditions affect the distribution and abundance of humans, environmental sources, arthropod vectors, and animal reservoirs for infectious agents. Each of these interacting components can be analyzed through statistical or simulation monitoring of case data, and enhanced using remotely sensed land use pattern data, that are integrated with other *in situ* data sources.

Environmental conditions have been characterized with satellite observations primarily by monitoring reflectance patterns in the visible and near-infrared spectrum. Spectral resolution has been coarse, historically relying on Landsat TM, MSS, AVHRR, and SPOT sensors for environmental monitoring. Yet, empirical studies indicate substantial success in characterizing environmental conditions conducive to disease transmission. For example, Beck and colleagues , used Landsat TM data to identify localized areas, based on vegetation and soil moisture characteristics that were at risk for Lyme disease in a spectrally complex residential environment. Radar and lidar have received substantially less evaluation in this field, although their potential utility in complex environments that experience substantial cloud cover during times of interest (e.g. tropical regions) has been recognized.

Moderate (> 20 m) to low (100-1000 m) spatial resolution imagery have been most commonly used to characterize environmental conditions, including land cover, elevation, temperature, and vegetation condition. Higher resolution imagery (<10 m) offers utility to identify individual features, especially those related to human activities and have been used to document the spatial distribution of human populations in regions undergoing rapid, often undocumented, development and land cover change. Temporal resolution of 1-16 days has proved satisfactory for many of the disease systems studied. In part this reflects the biological processes associated with pathogen amplification and population growth timeframe for insect vectors and other animals. Typically, a sufficient environmental signal has been detected to distinguish sites with increased likelihood for disease risk. Intra-day repeat interval for meteorological variables has currently been assessed using *in situ* monitoring systems for environmental conditions. Also, satellite-observation capabilities, in combination with *in situ* observations, allow for an integrated observational approach for use by emergency responders.

Future Needs

Primary requirements for future applications require sensors that characterize meteorological conditions (at least maximum and minimum surface temperature; daily precipitation, wind speed) and soil moisture on a within-day (2-4 times per day) basis as these appear to be major drivers of vector and animal population short-term demographic responses. These data serve as inputs to calibrate models of VBZ disease dynamics to identify time/space of risk. Many VBZ diseases begin in tropical and subtropical regions that can subsequently spread globally (e.g. Chikungunya virus). These regions often have substantial cloud cover making space-based monitoring of meteorological conditions difficult. Hyperspectral monitoring of land cover status is needed to improve characterization of vegetation classes and condition. Repeat coverage is on a weekly to approximately semi-monthly basis is appropriate as target populations typically respond to changing landcover conditions relatively slowly. For both types of data streams, moderate spatial resolution (20-500 m) captures much of the resolution needed for study on regional scales, though 20-100 m resolution would be preferable to resolve spatial details needed for calibration with VBZ disease models. A high resolution sensor (< 5 m) with multi-spectral capability to distinguish general land cover characteristics is needed to identify detailed patterns of human land use and distribution to locate at-risk populations. Such a system would need a low return rate (> monthly) to characterize changes in human population occupancy and use patterns.

OTHER IMPORTANT ISSUES

In addition to the specific mission recommendations, the panel discussed the importance of funding for research and applications aimed at societal benefits that are not specifically related to sensors, satellites, new remote sensing data, or particular missions. We specifically identified the importance of support for capture, synthesis, and analysis of remote sensing data aimed at understanding health and security problems. The principle U.S. governmental agency charged with human health research (National Institutes of Health) focuses largely on the "fundamental" determinants of causation and risk, with less emphasis on the more distal "environmental" causes that the panel considers critical. Even the Environmental Protection Agency has limited research funding opportunities available for investigation of remote sensing data that might affect human health. The Centers for Disease Control and Prevention (CDC) encourages studies that are aimed at remote sensing data applications to specific diseases, but historically they have not had extensive extramural funds for such research. Our panel considers the role of NASA, NOAA, and other partner agencies to be critical in funding environment and health scientists in the use of remote sensing data from partner agencies. The societal benefits that we all seek may not be achieved, even if the remote sensing data are obtained, unless there is substantial support provided for identifying and securing earth science determinants of the diverse health risks that can be understood.

Another aspect of this broad charge is to enhance epidemiological/disease surveillance efforts that use remote sensing data in a research and/or early warning program. We suggest that the societal value of such data will be enormously increased if support could be offered to health scientists who acquire and study remote sensing data because they understand how such insights can be used to analyze and anticipate disease outbreaks. These scientists lack adequate support because, they too often “fall between the cracks” of intellectual domains, research activities and associated funding. There is an important opportunity for NASA and NOAA to expand their research and application focus to explicitly involve studies of human health and security to a much greater extent. Such investment in research on these societal benefits will expand and enhance the value of these agencies to meeting the needs of citizens of the Unites States and the world.

Related to these other suggestions, which are critical to the panel’s discussions but not an explicit part of the study charge, is the role of aircraft (e.g., Europe’s MOSAIC program) and other non-satellite sensors in providing data for human health research and disease prevention. These data sources were not explicitly identified in any of the six disease areas, yet they are important to understanding patterns of other human health and security risks. Data collected through the use of aircraft supplement satellite imagery in several important ways: pre-launch sensor tests, post-launch ground truth, annual high resolution state surveys, emergency high resolution mapping (e.g. chemical spills, ocean blooms and forest fires), ground and ice penetrating sensors, below-cloud surveys, special field projects with combined flight level data and airborne remote sensing. These aircraft facilities and trained personnel must be maintained and enhanced to have a flexible resilient space-borne and airborne environmental monitoring system.

SUMMARY

The overall recommendations of the Panel on Human Health and Security are presented in Table 6.1. We identified many aspects of human health and security that should be enhanced by the availability, analysis and application of remote sensing data. We considered six broad areas of health effects mitigation that previously have been enhanced by space-based observations applied to such diverse health risks. Maintaining the types of remote sensing data that have allowed identification of environment-disease links, in time and space, is critical to the future understanding and forecasting of U.S. and global risks. In addition, new sensors that have finer spatial or spectral resolution have been identified and justified for the scientific and social benefits that will likely accrue. Relevant agencies should consider how to engage health and social scientists who are using satellite observations in a manner that encourages analyses that produce societal benefits. Such efforts should also actively promote exchanges of data and analytic methods that will foster interdisciplinary exchanges.

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7

Land-Use Change, Ecosystem Dynamics, and Biodiversity

OVERVIEW

Biota in land and marine ecosystems perform a myriad of functions that regulate climate and maintain habitable conditions for life on Earth. These functions include cycling water, carbon, nitrogen, and other nutrients among the land, ocean, and atmosphere; mitigating soil erosion, floods, and droughts; providing habitat to a diversity of species important for crops and medicines; and maintaining healthy cities and living environments for people. Ecosystems are under multiple pressures around the globe from accelerating changes in climate, land-use, and exploitation of ocean resources. These pressures affect resources critical for human welfare and, in turn, alter climate through feedbacks to the atmosphere. Satellite observations are critical to tracking changes in ecosystem condition, projecting future trajectories and resulting impacts on the economy and environment, and effectively managing ecosystems to mitigate negative consequences and enhance positive outcomes for society.

Long-term continuity of satellite observations of ocean and terrestrial productivity and land cover are key to determining their background variability in order to assess current changes and manage ecosystems. **The panel places its highest priority on maintaining and improving the long-term records for the productivity of terrestrial and marine ecosystems and for measuring land cover change at high spatial resolution.** Daily observations from space since the early 1980s have provided critical time series of ocean color and terrestrial productivity, and crucial and repeated high resolution images from the Landsat series have been the foundation for identifying changes in land cover, habitat fragmentation, human infrastructure, and other surface features since the 1970s. However, operational land observations fall outside of any agency's mandate despite the crucial need to ensure long-term continuity of these observations.

The next generation of satellite observations of ecosystems can transform understanding of the response of ecosystems to changing climate, land cover, and ocean resource use and underpin quantitative tools to improve ecosystem management. To help achieve this, **the panel has identified five missions that are critically needed.** These missions are described briefly below and then discussed in greater detail in the chapter**.**

- **Mission to observe distribution and changes in ecosystem function:** An optical sensor with spectral discrimination greatly enhanced beyond that of Landsat and MODIS is required to detect and diagnose changes to ecosystem function such as water and nutrient cycling and species composition. Such observations include nutrient and water status, presence and responses to invasive species, health of coral reefs, and biodiversity. We propose a hyperspectral sensor with pointability for observing disturbance events such as fire and droughts when and where they occur at higher temporal frequency.
- **Mission to observe extent and changes in ecosystem structure**: The horizontal and vertical structures of ecosystems are key features affecting carbon storage, disturbance effects, and habitats for other species. We propose radar coupled with lidar to address this need. Radar has the additional advantage of ability to make observations through clouds, a key constraint in many tropical regions for observing deforestation and re-growth.
- **Carbon budget mission**: The net exchange of CO_2 between the atmosphere and the land and the atmosphere and the oceans is the result of a complex set of biogeochemical processes that require

improved understanding to quantify and ultimately manage the global carbon cycle. Day and night measurements of column integrated CO_2 over land, oceans, and polar regions are key to improving our knowledge of the spatial and temporal patterns of biogeochemical processes leading to surface/atmosphere exchanges of CO_2. The measurement enables more complete understanding of carbon budgets because existing remote sensing capabilities only address photosynthesis and carbon exchange over sunlit regions, not the night-time return of CO_2 in respiration or air-sea gas exchange at high latitudes. We propose a lidar satellite mission to make diurnal, global measurements of atmospheric CO_2 in all seasons with a simultaneous measurement of pressure via column oxygen. Near simultaneous measurement of carbon monoxide (CO) to identify biomass and fossil fuel burning is also a key component of this mission.

- **Coastal ecosystems dynamics mission**: The coastal oceans of the world are an important yet poorly-observed component of the Earth system. Changes on land and in the open ocean are influencing the ecosystem services they provide to society such as the provisioning of high-protein food and healthy environments for recreation. Observations several times a day are required to capture the dynamics of coastal ecosystems. We propose a hyperspectral sensor in geosynchronous orbit over the Western Hemisphere.
- **Mission on biomass and productivity of the global ocean**: Quantifying the biomass and productivity of the open ocean with sufficient accuracy on climate-relevant time and space scales remains a significant challenge. We require improved optical measurements with far greater spectral resolution coupled and improved correction for atmospheric aerosols. These measurements will be used to study ocean ecosystems and their interactions with climate and global biogeochemical cycles. We propose a polar-orbiting, hyperspectral sensor through the addition of appropriate UV and visible bands to the polarimeter planned for the aerosol mission proposed by the climate panel (see Chapter 9).
- **Other priority missions from other panels**: Measurements within the purview of other panels are essential to interpreting ecosystem observations and integrating them into models. Changes in frozen and liquid water on land (soil moisture) are key measurements. Vector winds are key for analyzing ocean and coastal ecosystem dynamics. Temperature, precipitation, cloud cover, aerosols, sea surface temperature, and ocean topography are also vital observations.

While extremely important to the understanding of ecosystem changes, satellite measurements can only be fully exploited if complemented by essential ground and aircraft-based studies. A comprehensive strategy to observe and manage ecosystems includes *in situ* measurements of a wide range of variables such as pest outbreaks, fuel loads, biodiversity, agricultural yields, fertilizer application, and fluxes of atmospheric gases from land and ocean.

In the sections below, the considerations that led to the committee's conclusions and selection of mission priorities are discussed.

ROLE OF SATELLITES IN UNDERSTANDING ECOSYSTEMS

Among the major scientific advancements in the last few decades is quantitative understanding of the role that terrestrial and marine life play in regulating climate, protecting watersheds, providing diversity of species for crops and medicines, maintaining healthy environments, and performing many other services fundamental to human economies. Ecosystems regulate the amount of atmospheric carbon dioxide by storing carbon and cycling it among the land, ocean, and atmosphere. Biota also cycles nitrogen and other nutrients, essential for plant growth but detrimental when an excess of nutrients causes algal blooms harmful to coastal fisheries. In addition to the cycling of carbon and nutrients, plants cycle water between the soil, atmosphere, and water bodies. Vegetation mitigates floods and drought by buffering the flow of water to streams and rivers and enhancing the recharging of groundwater. The diversity of life found in ecosystems also benefits human society in multiple respects. Crop varieties depend on genetic diversity found in wild species, and the diversity of species maintains functioning

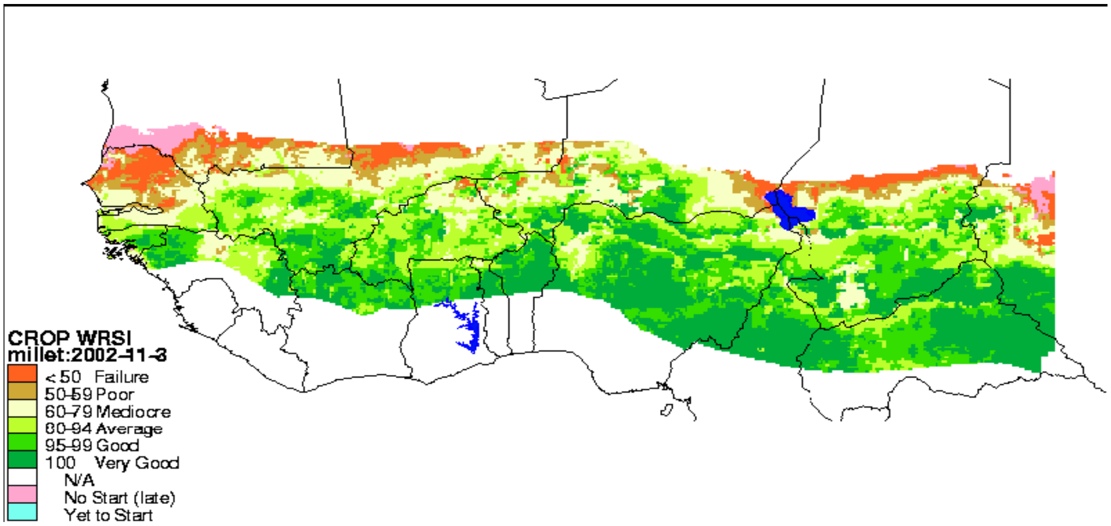

FIGURE 7.1 Map of the Water Requirement Satisfaction Index (WRSI) for the Sahelian countries of West Africa, 2002. Intervals of WRSI correspond to levels of crop performance and are derived from the Normalized Difference Vegetation Index observed by AVHRR and MODIS. Growing conditions for millet that year were especially poor for northern Senegal and southern Mauritania. Source: USGS/NOAA/FEWS NET Sahel (FEWS NET, 2004).

ecosystems in the face of disease, climate change, or other catastrophic events. These are a few examples of the essential role that ecosystems play in maintaining food production, water supplies, and the healthy living environments that underpin the human enterprise, in addition to the intrinsic and recreational value that many people place on healthy ecosystems.

Satellite observations of ecosystems have played a key role in developing the scientific understanding described above. One example is the Advanced Very High Resolution Radiometer, originally designed for meteorological applications and not intended to observe ecosystems. Its daily measurements of the red and infrared reflectances from the Earth's surface, however, have enabled a multi-decade time series of vegetation "greenness" against which changes in productivity from climate variability or other disturbances can be assessed. This capability has enabled applications such as the Famine Early Warning System (NRC, 2006) to identify locations susceptible to impending crop failure in Africa and weekly drought monitoring for the US partially based on satellite observations of vegetation health (http://www.drought.unl.edu/dm/monitor.html). As another example, Landsat observations since the early 1970s have been used for a myriad of scientific and practical applications, among them the ability to quantify tropical deforestation, identify where people are vulnerable to fire and floods, and to assess crop yields.

Optical, multispectral sensors have been the mainstay of remote sensing for ecosystems over the last two decades. Scientific advancements in applications of hyperspectral and active radar and lidar sensors hold promise for considerably enhancing the capabilities to observe and understand ecosystems, including invasive species, air quality, harmful algal blooms, and a host of other issues (e.g., Asner et al., 2004; Treuhaft et al., 2004). The ability to observe a full range of ecosystem dynamics is required in order to anticipate responses of ecosystems as land-use and climate change accelerate in the future.

Globally, nearly all ecosystems are under pressure from two trends. The first is pervasive land-use change and exploitation of land and ocean resources that are affecting most ecosystems, even in regions considered remote. The second is climate change, which is becoming increasingly evident in many regions. Some of the environmental issues that result from these two trends are widespread (e.g.

greenhouse gas emissions to the atmosphere) and some are specific to local conditions (e.g., habitat loss for endangered species). Addressing these issues requires approaches that couple the global trend (climate change, land and ocean use change, pollution etc) with the local particulars of soil, topography, and socioeconomic circumstances. Space-based observations have exactly this character: they provide a global picture, but they are spatially-resolved and so provide local particulars.

Ecosystem changes from climate change and human modification of the landscape and ocean are occurring in many parts of the world, notably coastal zones where much of the world's population lives, high latitudes where climate change is lengthening the growing season, and tropical forests, which are undergoing massive conversions for agricultural expansion and timber extraction. Even the vast, remote open ocean is experiencing large reductions in fish stocks due to harvesting. With accelerating changes in climate, land-use, and oceans over the coming decades, management of ecosystems to enhance and maintain provision of food, water, and other essential services for society is a critical challenge (Millennium Ecosystem Assessment, 2005).

The ability to manage ecosystems rests on having a scientific understanding of their role in the Earth system. Models suggest that changes in terrestrial and marine ecosystems accelerate the rate of CO_2 increase in the atmosphere and hence the rate of global warming. Yet, models disagree about the response of primary productivity to the competing or synergistic effects of temperature and moisture (e.g., Cox et al., 2000; Fung et al., 2005; Friedlingstein et al., 2006). Moreover, the continuing ability of the ocean to take up CO_2 is in question, as result of shifts in ocean circulation and temperature as well as ecosystem response. Disturbances and modification of the land surface and the ocean, natural or anthropogenic, are likely to further modify ecosystems and hence the carbon-climate system, beyond what these models project. Such changes may also increase the vulnerability of ecosystems to changing climate, moving ecosystems closer to thresholds beyond which there is no recovery and reducing their capacity to support life.

In summary, challenges posed by changing climate, land-use, air quality, invasive species, harmful algal blooms, and a host of other factors call for satellite capabilities that enhance our understanding of fundamental earth system processes and enable effective ecosystem management. The panel has identified a set of five priority satellite missions that, in combination with continuation of the long-term record and other supporting observations from missions recommended by other panels, will enable scientific progress and improved management of ecosystems.

INFORMATION REQUIREMENTS FOR UNDERSTANDING AND MANAGING ECOSYSTEMS

The world's ecosystems are subject to a variety of human-caused stresses including changes in climate, changes in the chemistry of the atmosphere and ocean, changes in frequency of severe storms, droughts and floods, and changes in land cover, land-use, and ocean use. These stresses can act singly or together to reduce the capacity of ecosystems to cycle water and nutrients or deliver food, water, or other ecosystem services. It is possible to halt and reverse ecosystem degradation (Millennium Ecosystem Assessment, 2005), and to enhance ecosystem services, with carefully planned actions that have their foundations in science. Sustainable management of ecosystems requires information about their ability to carry out functions such as nutrient and water cycling (ecosystem function) and the current state and future changes in the vertical and horizontal distribution of biomass within an ecosystem (ecosystem structure). Successful and adaptive management requires detecting trends early enough so that intervention can be successful, efficient, and inexpensive. Late remediation can be extremely or even prohibitively expensive.

Citizens, decision makers, and other types of stakeholders need several types of information to support effective responses. Changes in ecosystems have to be observed and documented, with, if possible, early detection of emerging issues. In order to evaluate management alternatives, there is a need to project ecosystem conditions under likely future scenarios of management, subject to changing climate, land-use, and other anthropogenic stressors. This requires both reliable information about the state of systems, and credible models of dynamics. The past decade's experience has shown that remote sensing data play a crucial role in developing, testing, and applying such decision-support models. Although many ecosystem issues develop slowly, there is also a need for remote sensing to provide decision support during and in the wake of episodic events. These include abrupt events like tropical storms and wildfire, as well as "slower" events such as insect outbreaks, harmful algal blooms, and droughts.

These strategic needs are encapsulated in the overarching questions (listed in Box 7.1) that guided the panel's consideration of which observational data will be required during the next decade.

BOX 7.1 STRATEGIC ROLE OF ECOSYSTEM SCIENCE AND OBSERVATIONS

Observing Conditions and Trends in Ecosystems. What are the current status and trends in the distribution of ecosystems, their productivity, degree of fragmentation by land-use, and other properties that affect the delivery of food, water, carbon storage, climate regulation, watershed protection, and other ecosystem services?

Projecting Future Trajectories. How will ecosystems and their ability to provide food, clean air and water, and healthy cities respond to future climate change, land and ocean use change, and other anthropogenic stressors? Are there critical thresholds in the ability of ecosystems to cope with anthropogenic stressors?

Managing Events. What are the opportunities for early detection, ongoing observation and management of extreme events such as hurricanes, drought and wildfire, insect outbreaks and flooding? What are the policy options for managing events that threaten human life and property? Can systems be managed to reduce their vulnerability before such events occur? Can ecosystems be managed to store larger stocks of carbon?

BACKGROUND ON OBSERVATIONAL NEEDS AND REQUIREMENTS

In order to provide the necessary information and tools to policy makers and other stakeholders, an observational strategy is required that will address the strategic needs described in the previous section. Based on the panel's assessment of observational needs for understanding and managing ecosystems, as well as previous analyses of needs and goals by the scientific community (NRC, 1999, 2001), the panel identified three broad scientific themes and key questions for prioritizing observational needs for the coming decade (Table 7.1).

TABLE 7.1 Key Questions for Identifying Priorities for Satellite Observations

Science Themes for Understanding and Managing Ecosystems	Key Questions
Disruption of the carbon, water and nitrogen cycles	How does climate change affect the carbon cycle? How does changing terrestrial water balance affect carbon storage by terrestrial ecosystems? How does increasing nitrogen deposition and precipitation affect terrestrial and coastal ecosystem structure and function and contribute to climate feedbacks? How do large-scale changes in ocean circulation affect nutrient supply and ecosystem structure in coastal and off-shore ecosystems? How do increasing inputs of pollutants to freshwater systems change ecosystem function? What are the management opportunities for minimizing disruption in the carbon, nitrogen, and water cycles?
Changing land and marine resource use	What are the consequences of uses of land and coastal systems, such as urbanization and resource extraction, for ecosystem structure and function? How does land and marine resource use affect the carbon cycle, nutrient fluxes, and biodiversity? What are the implications of ecosystem changes for sustained food production, water supplies, and other ecosystem services? How are interactions among fish harvesting and climate change affecting organisms at other trophic levels? What are the options for diminishing potential harmful consequences on ecosystem services and enhancing benefits to society?
Changes in disturbance cycles	How does climate change affect disturbances such as fire and insect damage? What are the effects of disturbance on productivity, water resources, and other ecosystem functions and services? How do climate change, pollution and disturbance interact with the vulnerability of ecosystems to invasive species? How do changes in human uses of ecosystems affect their vulnerability to disturbance and extreme events?

Disruption of the Carbon, Water, and Nitrogen Cycles

Terrestrial and marine ecosystems play key roles in the global carbon cycle through photosynthesis, respiration, decomposition, and carbon releases and uptakes following disturbances such as fire. All of these processes are altered by climate change and human uses of land and oceans. One of the major uncertainties in existing models is the future ability of oceans to take up carbon dioxide. Acidity of the ocean may be increasing more rapidly than previously thought (Orr et al. 2005), altering the ability of carbonaceous organisms to take up carbon especially at high latitudes. Understanding feedbacks between dust production and transport, ocean iron, and carbon export also remain a challenge in Earth science. In this same vein, the functioning of terrestrial ecosystems in a high atmospheric CO_2 and warmer atmosphere is unknown. The observations to test hypotheses about the spatial temporal pattern of contemporary oceanic and terrestrial sources and sinks for carbon dioxide are currently not available.

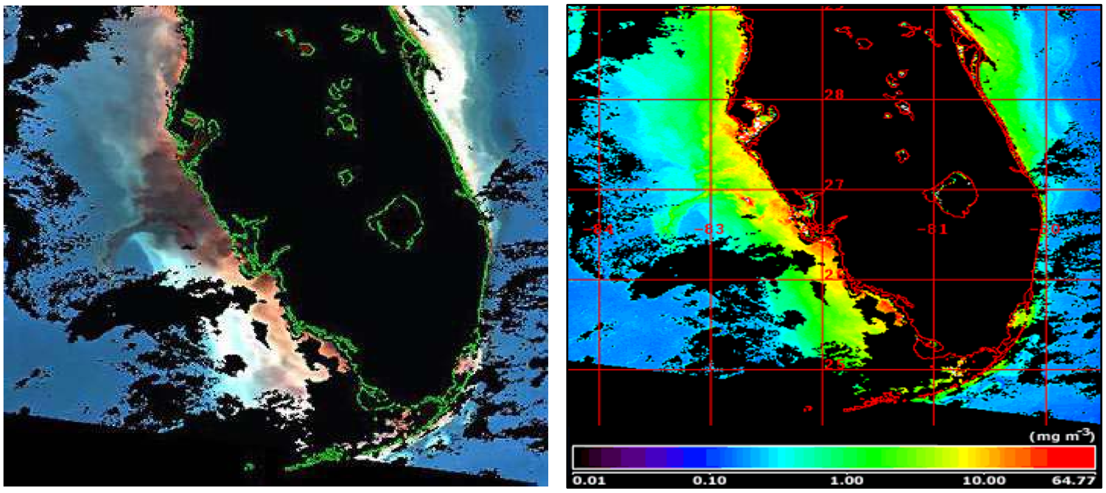

FIGURE 7.2 SeaWiFS captured these images of the Florida coast on September 17, 2001. In the left image, the colors red, green, and blue have been assigned to what the naked eye would see as green, blue-green, and blue. Clear blue offshore sea water appears blue, coastal water that is typically green appears red, and water with high levels of suspended sediment appears white. Water dominated by red tide appears dark gray. The right image is a false-color image showing milligrams of chlorophyll per cubic meter of sea water. SOURCE: http://earthobservatory.nasa.gov/Study/Redtide/.

Literature is growing on the interactions between the hydrologic and nitrogen cycles and climate change. (Melillo et al., 2002; Schlesinger and Andrews, 2000). Warming changes the water balance intrinsically, and even without changes to precipitation, it alters water availability, growing season length, susceptibility to disturbances including fire and insects, and thus a host of consequent ecosystem functions and services. Changes to the hydrological cycle are also profoundly disruptive to human societies through extremes such as floods and droughts. Space-based remote sensing has already proven critical to monitoring drought's effects on vegetation productivity, fire occurrences, soil moisture, and surface temperature. During the 1990s, drought-related wildfire increased land-to-atmosphere fluxes of carbon dioxide enough to significantly affect the global growth rate (VanderWerf et al., 2004).

While less starkly evident than drought effects, changes to the nitrogen cycle resulting from air pollution and agriculture also have major consequences, both for the carbon cycle (which is partly regulated by nitrogen) and for air and water quality directly (Vitousek et al., 1997). Evidence is growing that excess nitrogen deposition in terrestrial systems from fertilizers and other sources can affect the carbon cycle, as well as other ecosystem services through crop yield and biodiversity (which is reduced by excess nitrogen).

In coastal and marine systems, continuing fertilization of the coastal ocean through nitrogen-rich terrestrial runoff will affect both its productivity and ecosystem structure. For example, the occurrence of harmful algal blooms appears to be increasing in US coastal waters, and these blooms may be stimulated by increased nutrient availability. Conversion of estuaries and swamps to aquaculture is increasing throughout the world in order to provide more sources of protein. Reduction of large predators from marine food chains due to over fishing is cascading to lower trophic levels and hence carbon cycling.

Changing Use of Land and Ocean Resources

Conversion of lands for human use is essential for the human enterprise to grow food, build cities, and obtain other essential services. The increasing intensity and extent of human land-use is as global a change as changing climate. Harvesting of fisheries from the ocean and water quality impacts from coastal development are also leading to massive alteration of ocean ecosystems. Changing land and ocean use may increase the vulnerability of human populations and ecosystems to changing climate, moving ecosystems closer to thresholds beyond which there is no recovery. While each land and ocean use decision is unique, there are regional and even global trends that have cumulative impacts. The effects of changing land and ocean use range from the formation of large sources and sinks of CO_2, changes to hydrology and geomorphology, changes in landscape patterns affecting biodiversity, and a host of other effects (DeFries et al., 2004; Foley et al., 2005).

Remote sensing of land cover and ocean biomass change is crucial for both observing environmental change and as input in individual, local, national, and transnational decision-making. Satellite data, especially global, high resolution satellite data has proven its value and is now fundamental to studies of ecosystem change in academia, government, and the private sector. Improved sensors will increase the information content of ecosystem remote sensing from empirical measurements of type (more or less the current state-of-the-art) to measurements of function, such as nutrient cycling and carbon sequestration (achievable with current exploratory technologies). If these measurements of function are coupled with sufficiently-precise and globally extensive measurements of atmospheric CO_2, then the interaction between water, carbon, and other element cycles will be better understood.

Changes in Disturbance Cycles

Drought, wildfire, severe weather (tornados, hurricanes windstorms, ice storms), and insect outbreaks are major disturbances to ecosystems and disruptive to ecosystem services. Altered disturbance regimes occur in response to intensification of land-use and climate change. For example, dramatic increases in the growth rate of carbon dioxide in the atmosphere during 1997 were traced to wildfires in drought-affected areas of Indonesia (Page et al. 2002). Those wildfires, while possible because of the drought, were initiated by human activity and occurred mainly in regions where soil moisture was reduced because of land-use change. Disturbance regimes affect the marine and coastal realm as well: coral reef, estuarine, and coastal ecosystems were reshaped for decades to come by the 2005 hurricanes and tsunami. Even the crude prognostic models of disturbance and mortality tested in the early 2000s suggest that climate change could have its largest effects through ecosystem die-back and vegetation change, even without allowing for interactive effects of disturbance and land-use, as suggested in Indonesia, above. Observing disturbance cycles requires precise observations of ecosystems (i.e., effects of insects could be evident in hyperspectral data before many ground measurements would detect a problem), of disturbance (e.g., fire area and severity) and of consequences locally (e.g., smoke plumes, sediment-loaded waters, habitats for disease vectors) and globally (e.g., carbon dioxide trends).

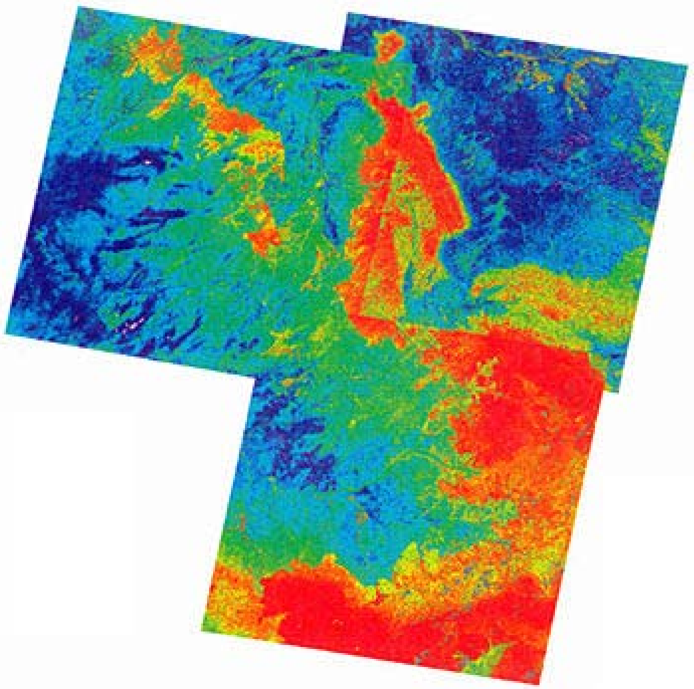

FIGURE 7.3 Between 1993 and 1995, an outbreak of hantavirus pulmonary syndrome (HPS) claimed the lives of more than 45 people in the southwestern United States. The 1991-92 El Niño had brought unusually high precipitation to the Four Corners region in 1992, which led to an increase in vegetation and a hypothesized increase in the rodent population that carried the hantavirus. Based on Landsat ETM+ satellite imagery, this map of the American Southwest shows the predicted risk of HPS in 1993. Red and yellow indicate high-risk areas, and dark blue indicates low-risk areas. SOURCE: NASA, (from Glass et al.), available at http://earthobservatory.nasa.gov/Study/Hanta/.

Summary of Data Needs

The challenges posed by changing climate, land-use, air quality, invasive species, harmful algal blooms, and a host of other factors call for the capability to: maintain and enhance a continuous observational record of ecosystem properties; observe episodic and extreme events such as fire, pest, and disease outbreaks when and where they occur; and begin records of critical ecosystem functions through measurements of carbon cycling, soil water, and vegetation structure. To perform these functions, the observation system or systems must provide an array of terrestrial, coastal, and open ocean satellite data products as illustrated in Table 7.2.

TABLE 7.2 Required satellite data products for understanding and managing ecosystems, land-use, and biodiversity

Terrestrial ecosystems	Coastal/open ocean ecosystems
-Distribution and changes in key species and functional groups of organisms	- Coral reef health and extent
- Disturbance patterns	- Photosynthesis
- Vegetation stress	- Sediment fluxes
- Vegetation nutrient status	- Phytoplankton community structure
- Primary productivity	- Algal blooms
- Vegetation cover	- Carbon dioxide concentration
- Standing biomass	
- Vegetation height and canopy structure	
- Habitat structure	
- Human infrastructure	
- Atmospheric CO_2 and CO concentration	

HIGH PRIORITY SATELLITE DATA RECORDS AND MISSIONS

In this section the panel identifies priority satellite missions to address the critical issues of climate and resource use-driven changes to ecosystems and the consequences for ecosystem functions. The suite of missions includes the ongoing, long-term data records and future missions with new technologies. This suite is designed to both detect and understand ecosystem change, and expand the information available to predict, manage, and enhance the provision of ecosystem services. The missions focus on quantitative observations of changing ecosystem processes, including ecosystem biogeochemistry, vegetation and landscape structure, water relations and disturbance patterns, which are the key diagnostics for a broad range of key questions (Table 7.1). While the missions are designed to be comprehensive, in the sense that they measure a suite of quantities for detecting changes in ecosystem structure and dynamics, they are focused on rigorous detection of impacts related to the carbon cycle, the water cycle, the productivity and management of ecological communities, and habitat characteristics. The focus in this set of missions is on terrestrial and coastal marine regions where human impacts and natural resource extraction are concentrated, as well as the open ocean, where the impacts are profound but less obvious to society.

We note that the space-based observations we recommend requires a mix of techniques. Some quantities can be directly estimated from radiances above the atmosphere using physical techniques. Examples include the hyperspectral measurement of leaf water content and phytoplankton fluorescence or the altimetric measurement of canopy height by lidar. Others are derived from the statistics of direct measurements, such as estimates of landscape heterogeneity used in conservation biology and ecosystem management, or the inference of surface sources and sinks of CO_2 from space-based measurements of column-integrated atmospheric CO_2. A third category includes quantities that result from using direct observations as inputs in physical, biological, or statistical models. An example of this approach is the estimate of carbon uptake and release through photosynthesis and respiration in marine or terrestrial systems, which are inferred from space-based estimates of photosynthetic light absorption. A final category includes quantities estimated from time series of measurements, which by their rate of change define some other process (i.e., the integral of photosynthesis over time can define biological productivity).

TABLE 7.3 Concepts for High Priority New Missions

Brief Description of Mission	**Variables**	**Type of Sensor**	**Coverage**	**Spatial Resolution**	**Frequency**	**Synergies with other panels**	**Related Planned or Integrated Missions (if any)**
Ecosystem Function: climate and land-use impacts on terrestrial and coastal ecosystems	*Terrestrial:* Distribution and changes in key species and functional groups of organisms; Disturbance patterns; Vegetation stress; Vegetation nutrient status; Primary productivity; Vegetation cover *Coastal*: Coral reef health and extent	Hyperspectral	Global, pointable	50-75 m	30 day, pointable to daily	Climate Health Solid Earth	HyspIRI
Ecosystem structure and biomass	Standing biomass; Vegetation height and canopy structure; Habitat structure	Lidar and InSAR	Global	50-150m	Monthly	Climate Health Solid Earth	DESDynI ICESat-II
Carbon Budget	CO_2 mixing ratio; CO concentrations	Active Lidar	Global	100 m strips	Diurnal—assimilated every 24 hours	Climate Chemical Weather	ASCENDS
Coastal Ecosystems Dynamics Mission	Photosynthesis; Sediment fluxes; Phytoplankton community structure; Algal blooms	Hyperspectral	Western Hemisphere	250 m	Several times/ day	Health Solid Earth Chemical Weather	GEO-CAPE GACM
Global Ocean Productivity Mission	Photosynthesis; Colored dissolved organic matter; Chlorophyll	Hyperspectral	Global	1 km	2-day global coverage	Climate (with additional UV/VIS bands on polari-meter)	ACE

Operational Satellite Records to Enhance and Maintain the Long-term Record on Ecosystem Dynamics

The currently available long-term record of ecosystem dynamics from a variety of sensors is critical for understanding and managing ecosystems in the coming decades. The panel places high priority on maintaining and enhancing this record. The role of multi-year time series in understanding ecological dynamics has long been recognized. From classic examples like the scientific exploitation of the Canadian Lynx-Hare data set, through the establishment of the Long Term Ecological Network (LTER Network), to newer classic papers using decadal eddy covariance record, long time series have shaped the field. Understanding of global-scale processes has been significantly advanced through long time series, including the ice core records, the Keeling record of atmospheric CO_2, the CZCS/SeaWiFS/MODIS records of ocean color, and the AVHRR and Landsat records of photosynthesis and land cover change. Long-term records of photosynthetic activity have enabled forecasts of impending food shortages, pest outbreaks, and other key ecological linkages with human health. To meet the challenges for understanding and managing ecosystems in the coming decade, the maintenance and extension of long-term ecosystem records is paramount. Here we briefly review critical applications, problems, requirements and opportunities.

There are three fundamental long-term satellite records of ecosystem dynamics, and each addresses a separate issue. First is ocean color, which began with the Coastal Zone Coastal Scanner and continues through with MODIS. These records link the considerable physical variability of the ocean to its intrinsic biological variability and are essential for understanding ocean processes and evaluating models. This measurement has been continually improved since the launch of CZCS in 1978. Further improvements are possible based on developments in scientific understanding, technology development and atmospheric correction (see mission recommendation below to enhance capabilities to monitor productivity in the open ocean). The second long record is the terrestrial "greenness" record that began with the insightful but unplanned scientific exploitation of the AVHRR sensor, and continues through MODIS and other satellite instruments. This record also has seen increasingly sophisticated applications, from a crude measurement providing an index of photosynthetic changes on seasonal and year-to-year time scales, to sophisticated retrievals of specific canopy properties used to estimate magnitudes and timing of critical ecosystem fluxes. The third record is the record of land cover change, derived mainly from Landsat, which has proved invaluable in quantifying deforestation and carbon emissions, urbanization, habitat fragmentation, habitat for disease vectors, and in managing natural resources and development activities. These three records have been used to address a wide range of scientific and practical problems and continue to gain in value with time.

These records detect changes that occur cumulatively over decades such as deforestation, and they gain in value with their increasing length. Several lessons can be drawn regarding long-term records. First, the records are--to a first approximation--independent of the sensor. All of these records have been constructed using multiple sensors over time. With care, accurate time series *can* be constructed using multiple sensors, thus allowing the use of improved technology and gaining more detail. Second, continuing legacy records requires care and effort. While records can be continued from one sensor family into another (AVHRR to MODIS and beyond to VIIRS on NPP and NPOESS), issues of bias, calibration and interference must be solved. For example, even within the AVHRR record, person-years of effort over a decade or more were required to construct a record correcting for instrument-to-instrument differences, shifts in overpass time within a mission, and atmospheric interferences. Even today, these corrections continue to be refined for some geophysical quantities.

The issue of deriving consistent, long-term climate records from operational satellite records has been the focus of several NRC studies over the past decade, (e.g. NRC, 2004). The issues and recommendations from these reports remain relevant today, and they have taken on new urgency with the planned launch of NPOESS in the next decade. Moreover, new issues have arisen, especially as sensor performance and operating scenarios for NPOESS have become clearer. In particular, the fundamental global measurement of ocean color from VIIRS will not meet science requirements given the current plans, creating the need for additional observational capabilities. Assuming that VIIRS will meet the threshold Environmental Data Record (EDR) requirements (and this is by no means assured), the NPOESS platforms will not collect regular lunar observations to characterize the performance of VIIRS. The need for such lunar observations on a monthly basis has been unequivocally demonstrated through analysis of the SeaWiFS record. Even this sensor showed significant and unpredictable changes in sensor response. If there had not been regular lunar observations, a consistent, multi-year time series could never have been developed. The Integrated Program Office for NPOESS has ruled out similar lunar observations for their platforms; thus new approaches must be found for a global-scale, multi-year, consistent time series of ocean color (see open ocean mission recommendation).

The Ecosystems panel recommends the following concerning long time series observations:

1. Long time series of critical environmental variables need to be maintained, with highest priority attached to records related to land and ocean primary productivity (ocean "color" and terrestrial "greenness"), and high resolution land cover. These records should be continued whenever possible with improved technology and improved scientific approaches.

2. Care should be taken when continuing and enhancing long term (legacy) environmental records to ensure backwards compatibility. That is, when new sensors are flown that use cheaper or safer technologies, or that improve on the geophysical products, the required steps should be taken to allow the legacy and new approaches to be cross-calibrated so the time series can continue without the injection of unknown error, noise, and bias.

Ecosystem Function Mission

Mission Summary - Ecosystem Function	
Variables	Distribution and changes in key species and functional groups of organisms; Disturbance patterns; Vegetation stress; Vegetation nutrient status; Primary productivity; Vegetation cover; Coral reef health and extent
Sensor(s)	Hyperspectral
Orbit/Coverage	LEO, global/pointable

New Science	Land ecosystem chemistry, diversity, leaf water stress; coral reef health and extent
Applications	Ecosystem interactions with changing climate, agriculture, invasives, disturbance, management, urbanization

Panel Synergies	Climate, Health, Solid Earth

From the priorities for new missions listed in Table 7.1, the first mission concept is aimed at detecting a suite of functional responses of ecosystems to direct human and climate impacts, and providing detailed information for improved management of these systems. This mission builds on the legacy of remote sensing of chlorophyll and visible reflectance and will use direct and inferential techniques for observing the spatial pattern of additional key functional properties of ecosystems. The properties targeted are identified as revealing critical responses for understanding climate and land/resource use impacts. Key properties are listed in Table 7.3 and include indices of both ecosystem composition (distribution and changes of key species or functional groups of organisms, disturbance patterns), ecosystem health and dynamics (leaf water stress, energy-water-carbon-nutrient fluxes). The mission focuses on terrestrial ecosystems but would also address coral reef health and extent.

Climate and land/resource use affect ecosystems by changing fluxes of matter and energy and in the longer term by changing the distribution of species and ecosystem types. For example, drought initially affects the magnitude and timing of water and carbon fluxes, causing plant water stress, and changes to leaf area. In the longer term, water stress induced-mortality and wildfire can cause ecosystem change, causing changes in species dominance towards more stress-tolerant or weedy species, or even ecosystem structural change with grasslands or shrublands replacing forests. Changes to chemical climate (ozone and acidic deposition) cause initial changes to the chemistry of leaves and then eventual ecosystem changes as more tolerant species replace natives. A terrestrial ecosystem mission must detect both the early warning signs of change through remote sensing of properties related to photosynthesis and other physiological processes.

The most promising technology for quantifying changes in ecosystem relies upon imaging spectroscopy (400-2500 nm) of the global land surface. The hyperspectral objectives are: canopy water content, vegetation stress and nutrient content, primary productivity, 2-D ecosystem heterogeneity, fire fuel load and fuel moisture content, and disturbance occurrence, type, and intensity. These measurements are made using a spectroscopic analysis approach afforded by observation of the full optical spectrum. The Hyperion sensor has shown that space-borne imaging spectrometer observations can advance ecosystem science by providing observations of canopy water, pigments, nutrients, carbon dioxide uptake efficiency, and species diversity (Asner et al., 2004). Hyperion data have been provisionally employed in a mainstream ecosystem dynamics model to simulate carbon sources and sinks in the northeast United States, showing substantial increases in accuracy over previous methods. Despite these early successes, Hyperion demonstrated that shortfalls in sensor uniformity, stability, and signal-to-noise performance limited its value in higher levels of ecosystem analysis. The accuracy, precision and autonomy of the measurement suffers when instrument performance is lower, as was the case with EO-1 Hyperion (15), or when the measurement is limited to multispectral sampling of the important wavelength regions.

The temporal and spatial resolutions required for ecosystem change studies depend on the scales of ecosystem variability. Ecosystems vary over multiple scales but detection of disturbance and landscape patterns, especially in intensively managed areas, implies relatively high spatial resolution (< 1 km). Studies of regional and global biogeochemistry have effectively used MODIS data at 250, 500, and 1 km resolution. Studies of community change and habitat heterogeneity require slightly higher resolution and discussions with investigators studying biodiversity and invasive species indicate a need for data at a resolution of 50-150 m. The target resolution of a global ecosystem change mission should be higher than MODIS (<250 m) but a determination of the exact resolution should balance the need for high temporal resolution and global coverage against spatial resolution, leaving the extremely high spatial resolution (which is required most often in specific locations rather than with global coverage) mission to the private sector and operational satellites. The temporal resolution needed for an ecosystem mission is high. For example, data from towers measuring gas fluxes show that the bulk of interannual variability in carbon uptake can be associated with changes in the timing of the growing season. Detecting climate-ecosystem interactions requires precise detection of the start and end of the growing season, as well as detection of stress episodes. The longest revisit time acceptable is a month or so, recognizing that this depends on cloud cover and other interferences and may not always be achieved. In order to combine repeat coverage with the ability to image “events” that could include large disturbances (e.g., wildfire) or abrupt seasonal transitions in critical areas, pointability is needed to occasionally allow more frequent revisits to critical areas. The science team would need to dynamically allocate observing time between the background program and targeted acquisitions.

Ecosystem Structure and Biomass Mission

Mission Summary - Ecosystem Structure and Biomass	
Variables	Standing biomass; Vegetation height and canopy structure; Habitat structure
Sensor(s)	Lidar and InSAR
Orbit/Coverage	LEO, global

New Science	Global biomass distribution, canopy structure, ecosystem extent, disturbance & recovery
Applications	Ecosystem carbon & interactions with climate, human activity, and disturbance (including deforestation, invasives, and wildfires); carbon management; conservation and biodiversity

Panel Synergies	Climate, Health, Solid Earth

Recent breakthrough technologies and retrieval algorithms for radar and lidar sensors are the most promising techniques for a globally consistent and spatially resolved measurement of forest 3-D structure and above ground woody biomass (AGB) from space. Global stock of AGB and its associated below ground biomass component (BGB) store a large pool of terrestrial carbon. The magnitude of this pool, its horizontal and vertical structure, and its changes as a result of natural and human-induced disturbances (e.g. deforestation, fire) and the recovery processes are critical for quantifying ecosystem change. Two technologies can provide this information.

Imaging radar sweeps the landscape with radio waves penetrating into the forest canopy and scattering from large woody components (stems and branches) that constitutes the bulk of AGB and carbon pool. Synthetic Aperture Radar (SAR) and Interferometric Synthetic Aperture Radar (InSAR) measurements are particularly suitable for estimating 3-D structure of forest ecosystems. InSAR can measure forest height with meters accuracy and the combination of polarimetry and interferometry can further improve estimation of three-dimensional forest structure. The sensitivity of backscatter measurements at different wave polarizations to woody components and their density makes low frequency (P-band or L-band) radar sensors suitable for direct measurements of live above ground woody biomass (carbon stock) and structural attributes such as volume and basal area. Current state-of-the-art radar technology allows these radar measurements from space with high spatial resolution (100-250 meter), day and night observational capability regardless of atmospheric conditions and cloud cover. Such a system could access information over forests globally, gauge the magnitude of forest biomass in boreal, temperate, and tropical regions, monitor and identify forest disturbance (fire, logging, deforestation), and characterize post disturbance recovery. L-Band InSAR, ideally with multiple polarizations, seems most suitable for measurements of ecosystem structure, particularly as such a mission would be synergistic with science goals of the Solid-Earth, Hydrology, Oceanography, and Cryosphere communities (see Chapter 8).

Lidar systems can use multi-beam laser altimeters, sampling the landscape and measuring with great precision the distance between the canopy top and bottom elevation, and the vertical distribution of intercepted surfaces. This measurement is the most direct estimate of the height and the vertical structure of forests. A lidar design with multiple beams and operating around 1064 nanometers can provide ~25 m spatial resolution and 1 m vertical accuracy, systematically sampling Earth’s surface, rather than imaging the entire surface, but providing a more direct retrieval than InSAR. The ideal Structure and Biomass mission would combine the two approaches, taking advantage of the precision and directness of the lidar to calibrate and validate InSAR, especially in ecosystem types where field campaigns have not occurred. The two sensors could fly on different platforms but the need for coincident observations separated not more than a few weeks is critical for using the lidar measurements to calibrate the radar measurements.

Several RFI responses call for a different strategy, and suggest a more regional focused approach, using a geostationary platform to achieve diurnal coverage. This is an interesting approach, pushing the data towards the “weather” time scales. Only a few ecosystem variables change fast enough to be detectable on sub-daily time scales, mainly those related to energy balance or planktonic dynamics, but the diurnal sampling would also allow detection of day-to-day changes and precise determination of growing season length. We adopt this approach for a Coastal Ecosystem Dynamics Mission (below) but focus on global LEO coverage as the primary terrestrial approach. While our first priority is a global mission, there should be continued study of the opportunities for ecosystem science from a geostationary experiment, along with identification of the key variables and science return from high-frequency sampling in time.

The panel also considered suggestions using multi-angle remote sensing, which can also retrieve certain ecosystem structure properties. While this approach is promising and could take advantage of instruments whose primary goals are atmospheric properties, it is more limited in terms of the range of ecosystems that could be sampled (these methods probably will not work well at high biomass levels) and in cloudy regions (such as Amazonia) (Bergen et al., 2006). These limitations keep us from recommending multi-angle instruments as a primary Structure sensor, but such a sensor would be a useful complement, and also provides certain variables (surface BRDF and albedo) that have wide application.

Terrestrial applications of a multi-angle sensor primarily designed for cloud and aerosol studies would be of great interest and are supported by the ecosystems panel.

Carbon Budget Mission (CO_2 and CO)

Mission Summary – Carbon Budget	
Variables	CO_2 mixing ratio; CO concentrations
Sensor(s)	Lidar
Orbit/Coverage	LEO, global
Panel Synergies	Climate, Chemical Weather

New Science	Active measurements of CO_2 mixing ratio at high spatial & temporal resolution capable during night and cloudy conditions, Carbon Monoxide as a tracer
Applications	High-resolution global distribution of carbon sources and sinks

Currently approximately half of the anthropogenic emissions do not stay in the atmosphere but are sequestered in the oceans and land. However, much uncertainty exists as to the mechanisms responsible for these sinks. A change in the current capacity of theses sinks will have important consequences for the future atmospheric composition and its associated climate forcing. Much of what we know today about how the atmosphere is changing and the rough geographic distributions of the carbon sinks comes from sparse (~100) *in situ* network of surface atmospheric sampling stations in remote island or coastal locations. Unfortunately, these observations are designed to capture large-scale changes in the background CO_2 and are too sparse in time and space to adequately reveal the sink processes, especially those on land, and the sensitivity of these processes to climate perturbations. This lack of knowledge has great impact on societal welfare. As nations seek to develop strategies to manage their carbon emissions and sequestration, the capability to identify and quantify the present-day *regional* carbon sources/sinks and to understand their climate sensitivity are central to prediction, and thereby, informed policy decisions.

Global measurements of column-integrated atmospheric CO_2 with sufficient precision and sample density for accurately recovering surface fluxes are only feasible from satellite platforms. The first step in inferring terrestrial ecosystem processes from atmospheric data is to separate photosynthesis and respiration: for this, diurnal sampling is required to observe nighttime concentrations resulting from respiration. It is also important to have measurements at all latitudes in all seasons, especially at high latitude land where temperatures are increasing and growing seasons are lengthening most rapidly, and over the unobserved Southern Ocean whose sink strength for the anthropogenic CO_2 is unresolved. It is also essential to separate physiological fluxes from biomass burning and fossil fuel combustion, thus requiring quasi-simultaneous measurement of an additional tracer, ideally carbon monoxide (CO). Socio-economic statistics on fossil fuel consumption is useful as a first estimate, but it is a less objective approach that is difficult to verify.

The needs for measurements of atmospheric CO_2 via an active (laser) sounder are specifically stated in national and international science documents. This mission is to characterize CO_2 sources and sinks on a sub-regional spatial scale in near real-time. Achieving this objective requires advances in measurement approaches and technology relative to current CO_2 missions. The current state-of-the-art for space-based remote sensing of atmospheric CO_2 is the Orbiting Carbon Observatory (OCO), scheduled for launch in 2008. OCO is a NASA ESSP mission for measuring total column CO_2 and O_2 by detecting spectral absorption in reflected sunlight. Although OCO will yield a vastly increased volume of data for characterizing distribution of atmospheric CO_2 and inferring surface sources and sinks, there are unavoidable physical limitations imposed by the passive measurement approach. These include: daytime/high sun only sampling, interference by cloud and aerosol scattering, and limited signal variability in the CO_2 column. A laser sounder mission, consisting of simultaneous laser remote sensing of CO_2 and O_2 (needed to correct for atmospheric pressure, topography and target height effects) would provide new active measurement capabilities to overcome the most serious of these limitations. Such a mission should provide: 1) full seasonal sampling to high latitudes, 2) day/night sampling, 3) some ability to partially resolve (or weight) the altitude distribution[1] of CO_2.

Lidar CO_2 and O_2 measurement should be complemented by a CO sensor, either as part of the CO_2 satellite, or by coordination with a "chemical weather" mission. CO is a major pollutant with a lifetime of one to three months and is important for atmospheric chemistry and air pollution studies. While CO is a valuable tracer allowing identification of biomass burning and industrial plumes for carbon science, CO_2 , which is chemically inert in the atmosphere, can be a valuable tracer of transport for chemists. The two measurements are highly synergistic and should be coordinated for time and space sampling, with the minimal requirement that the two experiments be launched close together in time to sample the same time period. Technology options for CO are discussed in the Weather chapter. Ideally, to close the carbon budget, we would also address methane, but the required technology is not obvious at this time. If appropriate and cost-effective methane technology becomes available, we strongly recommend adding a methane capability.

Improved measurements of CO_2 absorption line parameters are being conducted for OCO and are not expected to be a significant error source for the proposed mission. CO_2 lines are available in the 1.57, 1.60 and 2.06 micron bands that minimize the effects of temperature errors. The R24 line centered at 1.5711 microns is a good candidate because of its insensitivity to temperature errors, relative freedom from interfering water vapor bands, good weighting functions for column measurements, and high technology readiness of the lasers in this wavelength region. Temperature errors can be reduced to less than 1 K with the new sounding instruments and retrieval models under development for NPOESS. Pressure errors are addressed by a combination of simultaneous O_2 measurements or possibly with surface altimetry measurements from a pulsed lidar with advanced meteorological analysis for surface pressure. The on-board O_2 measurements can be based on LAS measurements on an O_2 absorption line in the 0.76 or 1.27 μm band.

Long term, accurate measurements of atmospheric CO_2 with global 'wall-to-wall' coverage will greatly enhance understanding of the distribution of sources and sinks for carbon dioxide in time and space. The measurements will allow a fundamental shift in our understanding of these processes, which are currently poorly understood due to a paucity of data. We believe that this observational objective is at reach in the next half-decade years and should a cornerstone in an Integrated Carbon Observing System. The Integrated Carbon Observing System should be built on high-precision long-term ground-based CO_2 observation networks and new active satellite observations which will fill in the gaps of the ground-based network in regions virtually impossible to sample.

The ground based CO_2 network requires a global, distributed, infrastructure capable to sustain atmospheric measurements of CO_2 and related tracers at the highest accuracy, with minimal risks of hiatus in data during several decades in the future. Components of this future infrastructure already exist in the US, with the NOAA-CMDL global air-sampling program, but in Europe they need to be integrated into a more harmonized observing system. Developing common methodologies, standards, data management systems, protocols and instrumentation will increase the cost-efficiency of the global *in situ* observations by avoiding duplication and by facilitating data sharing.

The coupling of this high-precision, high-volume data stream combining *in situ* and satellite observations with atmospheric inversion, data assimilation, and coupled atmospheric, terrestrial and ocean carbon modeling will enable us to quantify the sources and sinks at unprecedented space and time resolution. The final scientific outcome will be both greatly advanced understanding of the global carbon

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[1] It is not necessary to provide atmospheric profiles but rather the primary information is in the horizontal gradients of column integrated CO_2; however, most of the gradient is in the lower portion of the atmosphere and hence attaining sufficiently precise measurement of the gradients will require weighting the measurement to lower portions of the atmosphere.

cycle as well as the essential scientific foundation for making reasoned future projections of atmospheric concentrations of carbon dioxide. But even more importantly, we will have put in place one important brick in the infrastructure that will be needed for the next century to address changes in the environment of our planet.

Coastal Ecosystem Dynamics Mission

Mission Summary – Coastal Ecosystem Dynamics	
Variables	Photosynthesis; Sediment fluxes; Phytoplankton community structure; Algal blooms
Sensor(s)	Hyperspectral
Orbit/Coverage	GEO, coastal zones
Panel Synergies	Health, Solid Earth, Chemical Weather

New Science	Diurnal cycles of productivity and marine chemistry; coupling of land and open ocean
Applications	Harmful algal blooms, fisheries, ecosystem-based management, aquaculture, impacts of extreme events, productivity

A primary objective for observing coastal ocean regions is to determine the impact of climate change and anthropogenic activity on primary productivity and ecosystem variability. The high productivity of the coastal ocean supports complex food webs, and a disproportionate amount of the world's seafood is harvested from the coastal ocean. Harmful algal blooms in these regions introduce toxins with major human and ecosystem health consequences. These ecosystems are under enormous pressure from human activities, both from harvesting and from materials entering the coastal ocean from the land and the atmosphere. Climate change will also have significant impacts through changes in the hydrologic cycle (for example, peak runoff of the Columbia River is expected to be 6 weeks earlier in the year on average as a result of a warming planet), wind forcing (for example, shifts in the timing and intensity of upwelling-favorable winds), and agricultural practices (for example, fertilizer usage or irrigation). Many changes in the coastal ocean ecosystem are now beginning to be detected. Persistent hypoxic events or regions associated with riverine discharge of nutrients in the Gulf of Mexico, increasing frequency of harmful algal blooms in the coastal waters of the United States with extensive closures of coastal fisheries are just a few of the issues confronting the coastal ocean. The structure of coastal marine ecosystems is at the intersection of global-scale changes in the natural environment and intense human activity. The coastal ocean is an important and poorly observed component of the global ocean carbon cycle. About 25-50% of the global marine photosynthesis occurs in the coastal ocean although the coastal zone only represents 10% of the global ocean. The carbon flux from land to ocean can be significant: riverine flux to the coastal ocean of the United States is 10-30% of the atmosphere-land carbon flux. Carbon fixed through photosynthesis in the coastal ocean is strongly influenced by complex physical and biological controls on nutrient supply and light availability. The air-sea exchange of carbon dioxide depends on both physical transport processes in the atmosphere and ocean as well biological uptake. The interface between salt and fresh water plays a unique and important role in mediating the land/ocean interface and global biogeochemistry. Carbon exchange between the continental margin and the deep-sea (including land-to-ocean transport of carbon) is poorly understood because it is often small and, when larger, takes place episodically.

Recent work highlights the progress in estimating ocean primary productivity from satellite derived products of chlorophyll, phytoplankton growth rates, natural and harmful algal blooms, and carbon uptake (Behrenfeld et al., 2005). Remote sensing of the coastal ocean represents a unique challenge due to the small-scale spatial variability and elevated concentrations of dissolved organic carbon (DOC), detritus, and chlorophyll, which are difficult to distinguish because they all absorb light intensely in the blue end of the visible spectrum. However, DOC can be separated using observations in the ultraviolet (UV). The absorption of colored dissolved organic matter (CDOM) increases exponentially into the UV; absorption by particles contributes a smaller and smaller proportion of total absorption from blue to UV wavelengths.

Ocean data products include chlorophyll, particulate and dissolved organic matter, turbidity, phytoplankton growth rates, primary productivity, particulate inorganic carbon (organic sediment), and land ocean carbon fluxes are other target quantities detectable or inferable from ocean spectral measurements derived from the basic spectral signals. The instrument and mission characteristics for a coastal experiment are to a first approximation consistent with those for a land-oriented mission, but issues of spectral resolution, signal to noise, gain, and atmospheric correction would have to be studied.

Atmospheric correction, accurate instrument characterization and calibration, high signal-to-noise, and spectral range are all issues for a marine/coastal spectrometer. In coastal waters, the presence of absorbing aerosols and high in-water particle loads, which can invalidate the black ocean assumption for short NIR bands used in current atmospheric correction algorithms, complicate standard atmospheric corrections applied for current ocean color satellite observations. Negative water-leaving radiances for the 412 nm band (and at times for the 443 nm band) on SeaWiFS and MODIS occur frequently in coastal waters, because standard atmospheric corrections are not adequate for coastal waters, especially for near-shore waters and estuaries. However, intensive work in recent years with air-borne spectrometers has demonstrated the utility of this approach in coastal waters with complex optical signals. New methods for atmospheric correction have been developed, and they are proving to work in a variety of conditions.

Because of the complexity of both in-water and atmospheric optical properties in the coastal ocean as well as the requirement to estimate more of the constituents of the water-leaving radiance signal, we need a far more capable sensor than the SeaWiFS/MODIS class. Recent work from both *in situ* and airborne sensors have demonstrated that hyperspectral sensors can be used successfully in coastal environments and that detailed information on spectral shape as well as absorption at specific wavelengths can be used to extract quantitative information on the constituents of upper ocean. In fact, these measurements have shown that the traditional multi-band, absorption-based algorithms can fail in optically-complex waters.

Because many of the compounds of interest have strong absorption in the UV portion of the spectrum, it is essential that observations be made down to 350 nm. It will be necessary to extend the spectrum to about 1050 nm to observe the atmosphere against a "dark" background. We recognize that making observations in the UV will be challenging, given the small signal. Moreover, separating the effects of atmospheric aerosol (particularly absorbing aerosols) against an optically-complex ocean that will have variable levels of reflectance is also difficult. However, there has been considerable research in the past decade, and these challenges are being overcome.

These ecological and biogeochemical processes in the coastal ocean occur on small time and space scales, with a significant portion of this variability forced by solar and tidal cycles. For example, photo-oxidation of dissolved organic materials will need to resolve the diel variations in concentration to estimate the strength of this process. Many phytoplankton species that form harmful algal blooms show strong vertical migration on a diel basis, so multiple "looks" per day will also be necessary to resolve these processes. In summary, there is a close coupling between small spatial scales and short temporal scales in the coastal ocean. Current speeds tend to be higher near-shore as wind energy is distributed over a shallower water column than in the deeper, open ocean. Strong salinity discontinuities result in strong, transient frontal boundaries. Thus the science requirements drive the mission to a geosynchronous orbit to provide multiple viewing opportunities every day. Such a mission could also take advantage of cloud-free periods as well as "stare" at specific regions to increase the signal to noise ratio of the measurement. These capabilities are not available for polar-orbiting platforms.

Given these issues, we strongly recommend a geosynchronous mission focusing on the Western Hemisphere, rather than a complete global mission. Such a mission would study a broad range of conditions, including upwelling systems associated with eastern boundary currents off North and South America, areas with significant river inflow (e.g., Amazon, Mississippi, and Columbia), impacts for urban areas in the coastal zone, as well as relatively pristine area. This mission would focus on specific ecosystem and biogeochemistry questions in the coastal zone, rather than simply mapping global-scale processes. It would have the temporal and spatial resolution necessary to resolve critical processes in the coastal ocean, and it would have the sensor capabilities (SNR, spectral resolution, etc.) needed to de-convolve the complex atmospheric and ocean optical signals.

Global Ocean Productivity Mission

Mission Summary – Global Ocean Productivity	
Variables	Photosynthesis; Colored dissolved organic matter; Chlorophyll
Sensor(s)	Hyperspectral
Orbit/Coverage	LEO, global
Panel Synergies	Climate

New Science	New ecosystem products based on spectral matching techniques, including phytoplankton pigments and colored dissolved organic matter
Applications	Ecosystem-based management, productivity, regulation by different ocean nutrients (e.g., nitrate and iron)

Beginning with CZCS, global ocean color missions have dramatically increased our understanding of oceanic ecosystems and their relationship to climate and biogeochemical systems. Ranging from seasonal observations of the spring bloom in the North Atlantic, to the discovery of mesoscale fronts in the Equatorial Pacific, to long-term trends in ocean primary productivity, the succession of ocean color missions (CZCS to SeaWiFS to MODIS) have identified new processes based on continuous evolution in the technical capabilities of these sensors. As with the Coastal Ecosystem Mission, the Global Ocean Productivity Mission will focus on the quantification of upper ocean biomass and primary productivity and important aspects of ecosystem structure as they relate to changes in climate and their impacts on biogeochemical cycling (Behrenfeld at al ., 2005).

Although the per-area productivity of the open ocean is lower than in the coastal zones, its vast extent makes it an important sink of atmospheric carbon. The uptake of atmospheric CO_2 varies strongly on a regional and seasonal basis, but the long-term export of carbon from the upper ocean to its sequestration in sediments on the abyssal ocean are thought to be relatively constant. However, persistent shifts in ocean circulation and ecosystem structure may significantly alter this balanced system. For example, the Hawai'i Ocean Time-series station north of the island of Oahu has documented large-scale, multi-year shifts in the phytoplankton community from one that is regulated by nitrate availability to one that is regulated by phosphate. These shifts have significant impact on export rates to the deep ocean. Recent research by Behrenfeld et al. (2006) have demonstrated that differential regulation by iron and nitrate can be detected through remote sensing, and consistent, long time series of these measurements will greatly enhance the development of prognostic circulation/ecosystem models.

As with observing systems for coastal ecosystems, the next generation of global ocean color sensors will need far greater spectral coverage in terms of both resolution and spectral extent. The need to detect small, but significant, changes in the bio-optical properties of the upper ocean lead to more stringent sensor performance requirements in the face of complex atmospheric and ocean optical processes. Siegel et al. (2005) note that traditional wavelength ratio algorithms assume that the optically-active components of the ocean vary in a consistent manner. This assumption is not correct, however, and they propose the use of a "spectral matching" method. This new approach requires far more than the 7-10 bands of SeaWiFS, MODIS, and VIIRS, and it results in significantly different estimates of global primary productivity. If observations are extended into the 360 to 400 nm range, the spectral matching approach produces a more robust separation of CDOM from other constituents of interest. Expanded spectral capabilities will also enable the differentiation of different phytoplankton pigment groups. As many of these pigment-based groups have different roles in ecosystem processes and biogeochemical processes, there new measurements will support the development of more sophisticated models.

Along with improved measurements of standing stocks (chlorophyll, pigments, CDOM), an enhanced ocean color sensor will enable improved rate measurements. Behrenfeld et al. (2005) have shown that spectral matching techniques can be used to derive simultaneously absorption and backscattering properties which can be used to model both phytoplankton carbon (not just chlorophyll biomass) and growth rates. Bands to measure chlorophyll fluorescence (similar to those on MODIS) can be used to estimate the light-adaptive state of phytoplankton, and Behrenfeld et al. (2006) have shown that such observations can be used to detect iron stressed phytoplankton.

Improved atmospheric correction is essential for all of these observables, particularly in regards to aerosols which have temporal and spatial scales of variability that are similar to ocean properties. Bands should be placed near 1400 nm to account for turbid waters that are "bright" in the traditional atmospheric correction wavelengths around 865 nm. More sophisticated techniques are necessary to account for absorbing aerosols. Although bands in the UV wavelengths will help account for these absorbing aerosols, a polarimeter (as proposed for the climate panel) will provide knowledge of the height and total column thickness of these aerosols. This will build the basis for the next generation of atmospheric correction models.

Taken together, these requirements lead us to strongly recommend a global ocean productivity mission that would be accommodated as part of the aerosol mission recommended by the climate panel. The mission would be a polar-orbiting platform providing global coverage every two days, which is essential to provide the necessary temporal coverage, given typical patterns of cloudiness. The sensor would have at a minimum 20 selectable bands between 350 and 1400 nm, with 1 km resolution at nadir. The sensor would be able to tilt fore and aft to reduce the impacts of sun glint with SNR of about 1500:1 in the UV range, decreasing to 500:1 in the NIR. The sensor would need to have low polarization, as well as well-characterized (and low) cross-talk, stray light, and out-of-band spectral response. The mission would provide the necessary next-generation global ocean color measurements to significantly advance our understanding of the interplay between climate, biogeochemical cycling, and ecosystem structure in the upper ocean. With projected changes in atmospheric forcing as well as increasing acidity, it is essential that we develop more sophisticated prognostic models in order to understand the future role of ocean uptake in carbon cycling and ecosystem services.

Related Observational Needs for Climate and Other Variables

In order to understand the causes of observed ecological changes, and to assess the response of ecological processes to climate, a suite of climate and context variables must also be measured. These variables include many standard climate variables, proposed for measurement as part of the weather and climate requirements, or available through assimilation and analysis systems. The list for all ecosystems includes surface temperature, precipitation, and incoming radiation, especially in the photosynthetic wavelengths. For terrestrial systems, soil moisture is the critical variable linking climate and ecosystem response. For marine systems, sea surface temperature, ocean vector winds, and topography (for currents) are required because of the tight coupling of physical dynamics and marine ecosystems. Of this list, we call out several measurements, soil moisture, ocean topography and ocean vector winds, where the ecological requirements differ from or are more stringent than the corresponding physical (hydrological or atmospherically oriented) requirements.

The important hydrological control over terrestrial ecosystems is soil moisture and not precipitation, and current models are not good enough to infer soil moisture accurately from precipitation and temperature. Drought in the atmosphere becomes biological drought when soil moisture is depleted, triggering a range of ecological responses, from stress and reduced productivity to plant mortality, increased wildfire and insect damage and eventual replacement of ecosystem types. Moreover, changes in soil moisture will affect the amount of dust in the atmosphere which can then impact iron availability and hence ocean productivity. Models and observations suggest that climate warming will be accompanied by enhanced evaporation and hence reduced soil moisture and increased drought, at least regionally, and that trends in soil moisture will determine whether warming leads to increased or decreased plant growth.

The desired observation for ecosystems is "available water" which would be characterized under most conditions as the amount of water is the upper layers of the soil, although deeper groundwater can contribute in some conditions. There are two primary technologies for soil-moisture related experiments. The first uses either active or passive microwave energy, which is sensitive to soil moisture and surface wetness over land. Microwave techniques can have quite high spatial resolution, especially when active sensors are used, but are sensitive mainly to surface wetness and relatively insensitive to moisture deeper in the soil. A combination of frequent revisit times, ancillary precipitation data and assimilation modeling techniques holds high promise for inferring available water on ecologically relevant time and space scales. The alternative technique makes use of microgravity measurements to measure changes in mass distribution by measuring the Earth's gravitational field, as was done in GRACE. The GRACE-type measurement makes a relatively direct measurement of the ecologically relevant quantity-available water. However, the spatial resolution of the method is low and is constrained by basic physical principles.

Soil moisture is a key measurement for several disciplines, especially hydrology, where the primary discussion of this mission will be found. We strongly endorse a soil moisture experiment. In order to maximize the value of a soil moisture measurement for ecosystem science, it needs to resolve the time and space scales of variability relevant to ecosystem science. A temporal resolution (repeat sampling interval) of 3-5 days is needed to allow successful assimilation and inference of available water. This time interval is also critical for monitoring the development of plant water limitation and wet intervals associated with rapid and important soil activity. The spatial resolution required must correspond to scales of variability in terrestrial ecosystems, and in the soil moisture anomalies that affect them. This implies spatial resolution on the order of square kilometers to tens of square kilometers. These requirements should be considered in identifying missions to support hydrological science.

The coastal ocean ecosystem is characterized by intense variability at small time and space scales, which in turn are modulated by larger-scale shifts in global ocean and atmospheric forcing. For example, intense coastal fronts form at the interface between salt and freshwater, and these fronts are strongly affected by local winds and tidal currents. Moreover, coastal winds reflect the physical interactions or contrasts between ocean and land temperatures and fluxes, which cause intense variability in wind stress curl in time and space. Thus, studies of ecosystem dynamics and ocean chemistry in the coastal zone (within 100 km of land) require high-resolution (5-10 km) vector winds in order to infer relevant scales of variability in mixed layer depth, salinity and nutrients. These data will be assimilated into high-resolution models to provide the necessary oceanographic forcing fields for a range of coastal ecosystem models. A scatterometer mission is the only practical way to obtain these critical observations, and the scatterometer specifications must allow for the relevant spatial resolution, and temporal revisit time. Scatterometry plays an important role in weather and climate as well, but the physical and operational requirements in weather and climate may differ from those arising in ecosystem studies. High-resolution ocean topography is similarly needed to characterize tidal and other currents affecting circulation, and a wide-swath altimeter would provide these measurements. Again, the requirements for assimilation and analysis of ecosystem data may change the mission science requirements for an altimeter relative to those arising in the physical disciplines.

OTHER SPECIAL ISSUES

The Role of Suborbital Remote Sensing in Ecosystem Measurements

Many problems in ecosystem science require global data, but significant issues require high resolution, timely information in a specific area. In addition, some quantities and regions are difficult to observe from space because of cloud cover, aerosol interference, or other problems. During the past decade, several sensors have been developed, often for aircraft testing of orbital mission concepts, which can fly on manned or unmanned aircraft. Although there are a significant number of such sensors in existence, access to them is not widespread and few are in operational use. In surveying the community for research needs, it became clear that a range of science applications can be met efficiently and cost-effectively with aircraft-based instruments. Especially where there is a demand for data with a high spatial resolution but not global coverage, aircraft allow an attractive balance of low development cost, simple maintenance, and ready deployment in response to specific conditions or events. Example applications include analyses of ecosystem dynamics following disturbance from fire or flood, sediment transport and carbon dynamics at landscape scales, and management of invasive or harmful species in fragmented landscapes.

The ecosystem panel recommends that NASA, in partnership with NOAA and USGS, consider the transitioning of NASA satellite technologies to operational airborne platforms. Example technologies that would have high value in operational airborne applications include hyperspectral sensors for land and coastal applications, canopy remote sensing using radar or lidar, and lidar sounding of CO_2 and other trace gases. If such sensors were available at reasonable cost, they would be well-positioned for applications by NOAA for coastal management, USGS for mapping of land resources and water quality, and by university-based researchers for addressing a range of science questions. Opportunities for industry and small businesses to participate could also be included in a coherent technology transfer program. Links to the planned NSF NEON and existing LTER programs are also possible. Aircraft platforms and low cost-high performance sensors would be a powerful combination. Sensors that could be deployed on commercially available aircraft, as does NOAA's trace gas sampling flask package (which is now manufactured by small businesses), would increase the utility of such sensors. An effective program would develop robust, readily deployed sensors for critical applications, and, likely, transfer or license the technology to private firms, for use in both research and applications.

There is a possible marine counterpart. Many marine management questions are related to fisheries and higher trophic levels, yet remote sensing really only directly detects phytoplankton. However, acoustic remote sensing in the water column may be able to at least quantify biomass (fish) by size class and so provide an *in situ* complement to space-based remote sensing of marine ecosystems. Such autonomous technology is advancing rapidly and could be considered a marine counterpart to airborne suborbital instruments. Such *in situ* sensors would require telemeter data back using space-based links and so would be integrated with a space-based system. The planned NSF ORION as well as the Argo program can incorporate such sensing technologies.

The ecosystems panel recommends that a study be done of the possibilities and mechanisms for more effective complementing of NASA's space mission with advanced suborbital systems, including aircraft and sea-borne systems.

International Collaborations

Space-based exploration of the earth system is an increasingly global venture, with innovative technologies and strong implementations coming from a range of countries. NASA's plans for space-based sensors for ecosystem, land-use, and biodiversity studies should be complementary to those of other countries, with a sophisticated investments in, where appropriate, sharing development, sharing data, and coordinating timing and continuity. On the other hand, NASA needs to take leadership on the missions that take best advantage of its capabilities and the science requirements of the U.S. scientific community. In the area of ecosystem, land-use, and biodiversity critical opportunities for synergy include the international suite of high resolution (10-50 m) sensors to provide global coverage of Landsat-like observations.

End-to-end Systems for Integrating Observations in Management Decisions

Data from satellites are often essential for solving real-life problems and answering important questions in ecosystem, land-use, or biodiversity science. But, they are rarely sufficient. The information necessary to comprehensively address these issues typically comes from diverse sources, integrated in a model or another decision-support tool. In planning the future of U.S. remote-sensing science, it is critical to identify the additional resources necessary to transform remote sensing products into integrated decision support products. In many cases, NASA may need to fund the development of these additional resources, or it may need to work with partners to insure their development. For a particular problem, these resources might include ground-based observations, simulation models, or tools to support public outreach. History makes it clear that modest investments in these capabilities can be the difference between a successful but sparingly-used satellite data set and one that is a core element in a major set of environmental management decisions. Real applications almost always depend on the tools to get from the observations to the interpretations (NRC, 2003).

Our European colleagues acknowledge the importance of viewing the system end-to-end. The treatment of CO_2 observations is a particularly relevant point following our recommendation for an active CO_2 mission. The European Centre for Medium-Range Weather Forecasts (ECMWF) is currently treating carbon dioxide in their weather models using a surface condition monthly climatology of land fluxes and the Takahashi CO_2 surface partial pressure maps for ocean fluxes. CO_2 is transported horizontally and vertically by the model dynamics and parameterizations. The 4-dimensional variational data assimilation system treats CO_2 on the same footing as water vapor, cloud variables, ozone, etc. It is currently operational assimilating ~330 AIRS channels including 60 channels particularly sensitive to CO_2. At this time (September 2006), ECMWF is currently running a 60-90 day assimilation to test the system. In addition, their partners at Le Laboratoire des Sciences du Climat et de l'Environnement (LSCE) have developed and are currently testing a variational method to use the daily analyses to invert for monthly/seasonal-mean sources and sinks.

BOX 7.2 FUTURE PLANS BY EUROPEAN CENTER FOR MEDIUM-RANGE WEATHER FORECASTING FOR INCORPORATING CO_2 IN WEATHER FORECASTING

- **2007.** In the first half of 2007 European Center for Medium-Range Weather Forecasting (ECMWF) will do an extended assimilation of weather and CO_2 for the period 2003-2004. In the second half of 2007, ECMWF will upgrade the system to include CO_2 in the land-surface model rather than use climatologies.
- **2008-10.** ECMWF will merge the CO_2 system with the two other systems for aerosol and reactive gases
  - —Reanalysis of AIRS and SCIAMACHY data;
  - —Prepare to use OCO, and
  - —Prepare for operational CO_2 transition in May 2009 through adding the assimilation high temporal tall tower data.
- **2010-2012**. ECMWF will run the system behind real-time, ~3-6 months late, to produce operational estimates of sources/sinks based on IASI, CrIS, OCO, and GOSAT. Prepare to incorporate CO_2 data from an active system.

In situ Observations

Effective application of the data from earth observing satellites for questions in ecosystem, land-use, and biodiversity science depends on the availability of a diverse array of high-quality datasets. Some of these can come from space-based instruments with a primary focus on science questions from other disciplines. Others must come from ground-based observations (e.g., weather, pest outbreaks, biodiversity surveys), atmospheric measurements (e.g., CO_2, N_2O, NO_x, CO, CH_4), or statistical databases (e.g., fisheries landings, harmful algal blooms, agricultural yield, timber harvests, fertilizer application, or livestock stocking levels). Developing ways that ensure both the availability and the quality of these key *in situ* observations needs to be a part of the NASA investment in Earth science.

The data from Earth-sensing satellites can be fully exploited only if the satellite missions are designed as a package that includes essential ground and aircraft-based studies (see “Carbon Budget Mission (CO2 and CO),” for example). These range in intent from algorithm development to studies designed to provide a broader context for the remote-sensing results. In many cases, modest investments in ground-based studies can dramatically amplify the value of remote sensing information. Often, NASA is the only federal agency positioned to make the investments that take advantage of the complementary nature between satellite and ground-based observations.

Synergistic Observations from Other Panels

Many of the observations and technologies recommended by this panel intersect with requirements identified by other panels (as listed in Table 7.3). For example, the Ecosystem Structure and Biomass Mission is synergistic with the needs from the Solid-Earth community for radar measurements. To the degree that multiple objectives can be achieved with suites of observations from the same sensor, the panel fully supports the approach of identifying opportunities for synergy with other panels.

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8
Solid-Earth Hazards, Natural Resources, and Dynamics

OVERVIEW

The solid-Earth is the repository of the raw materials that support life. Further, it is the continual discovery of new Earth resources, or new approaches for exploitation of known resources, that sustains societal functioning. Our resources and habitat are ultimately the result of dynamic processes within our planet, processes which are also a source of danger. Hundreds of thousands of lives will be lost in the next century from catastrophic earthquakes, explosive volcanic activity, floods, and landslides. Investment of billions of dollars will be needed to mitigate losses from these disasters as well as from slower ongoing processes such as land subsidence, soil and water contamination, and erosion. Fundamental scientific advances are needed to inform these investments to protect human life and property. These scientific advances require new global observations to quantify rates of accumulation of crustal stress and strain and the evolution of land surface chemistry and topography. Detailed remote sensing of the evolution of topography and composition of the Earth at regional and global scales and decadal timescales will lead to fundamentally new understandings of our planet, essential to inform decision-makers and citizens alike.

The continual change of the solid-Earth on a wide range of time scales necessitates the use of global observations to develop the knowledge necessary for mitigation of natural hazards. For example, the earthquake cycle in seismically active regions typically has characteristic timescales of centuries to millennia. Thus, observations at any one place over intervals of days to decades, or even over a century (the length of the instrumental record), often capture only a tiny fraction of the cycle. However, when studied over the whole globe, the frequency of events is high, and the study of events in one location can provide the knowledge needed to save lives in other locations. For example, observations of tsunamis generated by earthquakes in Indonesia and South America help us to better assess the earthquake and tsunami risk to the Pacific Northwest. Observations of seismically-induced landslides in Pakistan help us to understand similar risks in California. Observations of volcanic eruptions and their precursors in Kamchatka and the Philippines help us to significantly improve our forecasting of volcanic hazards in the United States. More precise knowledge of the timing and likely impact of these sudden catastrophes, as well as constraints on the processes driving slower changes that occur in Earth's surface chemistry and topography, will increasingly have geopolitical implications. We cannot afford to miss opportunities to make space-based observations in areas where land-based observations are unavailable or are impractical due to access restrictions of a physical or political nature.

In this chapter, the panel has identified the three highest-priority satellite missions essential for advancing the knowledge base that society needs to manage, understand, forecast, and mitigate natural hazards, to improve discovery and management of energy, mineral, and soil resources, and to address fundamental questions in solid-Earth dynamics. The first mission addresses when, where, why, and how much the surface of the Earth is deforming. This surface deformation can be a measure of the accumulation and release of stress and strain through the earthquake cycle, or it can be the harbinger of catastrophes such as volcanic eruptions or landslides. The second mission addresses how and why Earth's surface composition and thermal properties vary with location and time and has implications for resources, susceptibility to natural hazards, and ecosystem health. The third proposed mission seeks to determine much more accurately the topography of all seven continents, allowing improved prediction of flood inundation and landslide likelihood, as well as providing an understanding of how this topography evolves over time.

To put these missions into perspective, it is important to realize that we now have the capability to monitor the events and processes responsible for natural hazards in real-time, allowing the possibility for short-term forecasting of their occurrence. Tremendous advances in computational power provide the platform to model complex systems over a variety of timescales. What we lack are sufficient quantitative observations of the relevant physical processes. If such observations are combined with realistic parameterizations of Earth material properties over the spatial scales needed to understand events triggering catastrophic hazards, as well as the processes that unfold after initiation, we will be able to improve forecasting for protection of property and human lives. The three missions required to implement this vision are summarized below and discussed in more detail in the remainder of the chapter..

- **Mission to monitor deformation of Earth's surface:** The first priority for solid-Earth science is a mission to observe and characterize sub-centimeter-level vector displacements of Earth's surface. Surface deformation is a visible response to processes at depth that drive seismic activity, volcanism and landslides. Local subsidence and uplift from groundwater extraction and recharge and hydrocarbon production are also visible in maps of deformation.

Requirements: An L-Band (1.2 GHz) InSAR mission meeting the science measurement objectives requires a satellite in a 700-800 km orbit maintained to repeat within a 250 m tube. The mission should have a 5 year life time to capture time-variable processes and to achieve improved measurement accuracy by stacking of interferograms to remove atmospheric noise. Measurements at L-band minimize temporal decorrelation in regions of appreciable ground cover. Two sub-bands separated by 70 MHz allow correction of ionospheric effects. Left- and right-pointing images on both ascending and descending orbits are needed to obtain vector displacements. An eight day revisit interval balances complete global coverage with frequent repeats. The baseline mission, providing fundamental constraints for questions related to volcanoes, earthquakes, landslides, resource production, and ice sheet dynamics, requires a single polarization antenna; a multiple polarization capability would add determination of variations in ecosystem structure to the science return (Chapter 7).

- **Mission to observe surface composition and thermal properties:** Changes in mineralogical composition affect the optical reflectance spectrum of the surface, providing information on the distribution of geologic materials and also the condition and types of vegetation on the surface. Gasses from within the Earth, such as CO_2 or SO_2, are sensitive indicators of impending volcanic hazards, and plume ejecta themselves pose risk to aircraft and to those downwind. These gasses also have distinctive spectra in the optical and near IR regions. Thus, our second priority is a sensor that can resolve both in finely detailed spectra.

Requirements: For this mission, two pointable sensors on the same platform are required: an optical hyperspectral imaging sensor operating in the 400-2500 nm region and a multispectral sensor operating in the 8-12 μm thermal infrared region. The hyperspectral sensor, with spectral discrimination greatly enhanced beyond Landsat and MODIS-class sensors, would make key observations for resource exploration, soil assessment, and landslide hazard forecasts. The combined, pointable hyperspectral and infrared sensors would greatly improve volcano monitoring and eruption prediction and aid in prospecting for resources and mapping long-term changes in physical and chemical properties of soil, as well as being essential for characterizing ecosystem changes.

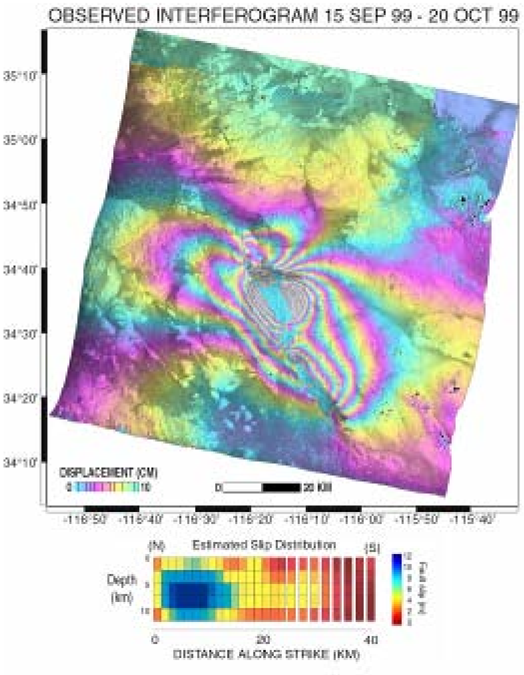


FIGURE 8.1 *Top:* Deformation resulting from fault slip that occurred in the 1999 Hector Mine earthquake in the Mojave Desert, California is revealed in this Synthetic Aperture Radar interferogram. An interferogram is generated by taking the difference in phase of two radar images taken from the same location in orbit, but at two different times (here, September 15, 1999 and October 20, 1999). Just as the interference fringes seen on an oil slick reveal small changes in thickness of the oil film, the interference fringes shown represent small changes in distance from the satellite to the ground. *Bottom:* The cm-level sensitivity to the surface deformation pattern permits a determination of the distribution of slip many km below the surface, yielding unprecedented insight into earthquake physics. (image from Zebker, et al., 1999). The C-Band satellite used to make these observations performs adequately in desert regions, longer wavelength L-band InSAR satellites are needed to obtain similar information in vegetated areas. In addition, because of the 5 weeks that elapsed between acquiring observations, the image of coseismic deformation is corrupted by the postseismic deformation that occurred after the earthquake (see Sidebar 8.1). Finally, even though this is a desert region, the image is degraded by noise due to atmospheric effects that could be removed if many more observations could be stacked.

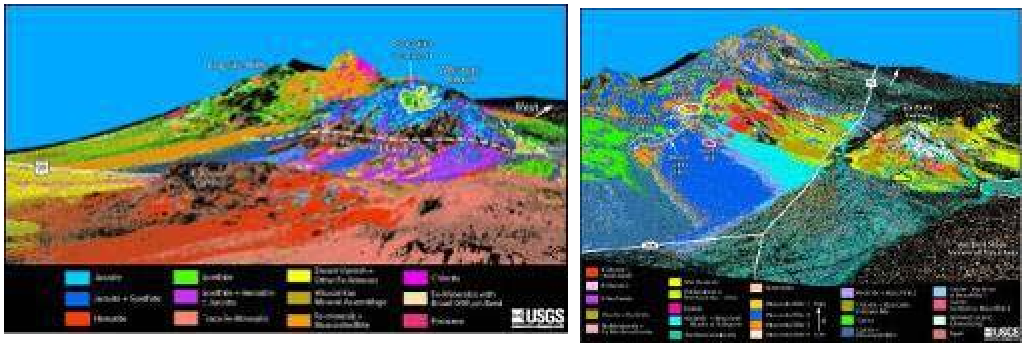


FIGURE 8.2 Significant differences in surface chemistry in a mining region caused by natural and anthropogenic processes can be monitored by satellite. For example, these hyperspectral images of Cuprite, Nevada, acquired by the AVIRIS satellite, overlain on a digital terrain model were processed a) to identify iron mineralogy; b) to identify hydroxide- and carbonate-bearing minerals. The dominant mineral in each pixel is identified and color coded. Both topography and mineralogy control formation of alteration minerals that contain hydroxides and carbonates, largely because such alteration can create the most acidic waters on earth. Such drainage flows downhill and creates surface alteration zones. As humans alter larger and larger regions of Earth's surface, documenting such impact through satellite imaging will be of use in assessing the impacts. (from Swayze et al., 2006)

- **Mission to measure high-resolution (5 m) topography of the land surface:** Many hydrologic and geomorphic processes are revealed in detailed topographic data. Our third priority is to develop a mission to determine Earth's elevation at every point on land to the sub-decimeter level, approaching the quality of information that we already have for Mars. Our recommendation is primarily for a first-epoch mapping of Earth's surface. This would set the stage for repeat imagery, which would allow the quantification of rates of many natural and anthropogenic processes such as top soil loss and wetlands disruption and degradation,

Requirements: A promising technology for high-resolution spatial topographic mapping is imaging Light Detection And Ranging (lidar). Two-dimensional surface coverage can be accomplished using multiple-beam laser systems, by the use of scanning platforms, and/or by using pixilated detectors in which each pixel has an associated time of flight chip that provides a measurement of elevation. Providing 5 m resolution topography at decimeter accuracy would facilitate forecasting of landslides and floods, as well as allow fundamental advances in geomorphology.

While these three missions are the primary recommendations and focus of this chapter, we also note several other high priorities for solid-Earth science. These include the measurement and determination of the terrestrial reference frame and the use of suborbital technology for measurements that must be made either locally or at closer distance and time intervals than is allowed by space observation. In addition, two space missions addressing spatial and temporal variations in the gravity field of primary interest to other panels are also of interest to solid-Earth science. Important science needs for geomagnetism will be met by international partners.

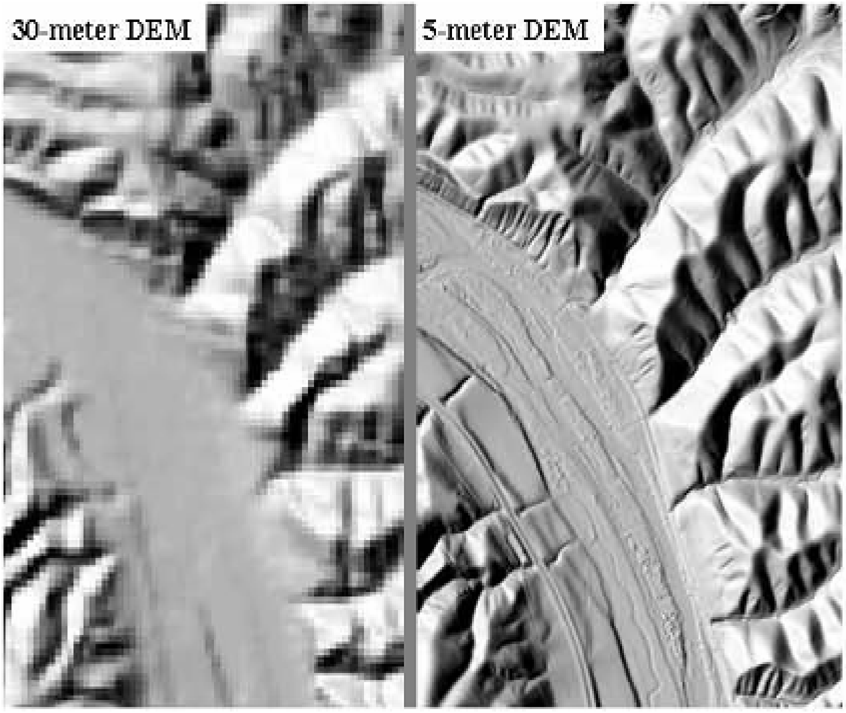


FIGURE 8.3 Mapping natural hazards and understanding the processes that shape Earth's surface, both require high-resolution topographic data. The figures above show shaded-relief maps of California's Salinas River and surrounding hillslopes. The left-hand image shows the finest resolution that is currently available over much of the Earth's surface (30 meters). The right-hand image shows the same scene, at the resolution that is achievable with lidar mapping from space (5 meters). Mapping landslide and flood hazards in this landscape is achievable with 5 meter topographic data, but impossible with 30 meter data. SOURCE: Courtesy of J. Taylor Perron, University of California, Berkeley.

- **Requirement for precise measurement and maintenance of the terrestrial reference frame:** The geodetic infrastructure needed to enhance, or even to maintain the terrestrial reference frame is in danger of collapse (cf. Chapter 1). Improvements in both accuracy and economic efficiency are needed. Investing resources to assure the improvement and the continued operation of this geodetic infrastructure is a requirement of virtually all the missions for every Panel in this study. The terrestrial reference frame is realized through integration of the high precision networks of the Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR). It provides the foundation for virtually all space-based and ground-based observations in Earth science and global change, including remote monitoring of sea level, sea surface topography, plate motions, crustal deformation, the geoid, and time-varying gravity from space. It is through this reference frame that all measurements can be inter-related for robust, long-term monitoring of global change. A precise reference frame is also essential to interplanetary navigation and diverse national strategic needs.
- **Important suborbital missions:** Two kinds of suborbital missions would provide important information about the Earth's interior, gravity, and magnetic properties. (1) Development of an Unmanned Aerial Vehicle (UAV) capability will allow temporally dense InSAR coverage of deformation associated with earthquakes and volcanoes and also provide high resolution measurement of spatial variations in Earth's gravity field with better accuracy than from space. Such observations would enhance knowledge of geologic structures where higher order gravity field expansion terms are too weak to be reliably observed.

(2) Magnetic studies from balloons ("stratospheric satellites") could lead to new understandings of Earth's crust.

- **Other important space missions:** Two missions selected as high priority for other panels would greatly enhance our understanding of processes acting within the solid-Earth.. These are: (1) Measurement of temporal variations in Earth's gravity field at improved resolution via an improved version of the GRACE mission, which would provide important constraints on the rheology of Earth's interior. This would lead to improved models of the convective processes driving plate tectonics and hence nearly all active deformation, as well as providing fundamental constraints on processes related to movement of water masses for hydrology and oceanography; (2) Measurements of sea-surface topography via radar altimetry (see Water Panel) would allow an order of magnitude improvement in the size of seamounts on the ocean floor that could be discovered and analyzed. This would both reduce navigation hazards and increase our knowledge of volcanic processes. Although these missions are not the highest priority for our Panel, they are of substantial value. Important observations of temporal and spatial variations in Earth's magnetic field will be provided by international missions.

In summary, the challenges posed by resource discovery and production, by forecasting, assessment, and mitigation of natural hazards, and by advancing the science of solid-Earth dynamics, call for ongoing investment in satellite capabilities. The panel has identified the above set of three priority satellite missions that, in combination with a robust global geodetic network and a continuation of the long-term instrumental record and other supporting observations from missions recommended by other panels and flown by other countries, will enable scientific progress and improved strategies for management of solid-Earth hazards, resources, and dynamics.

THE STRATEGIC ROLE OF SOLID EARTH SCIENCE

The events of the past few years – for example, the volcanic unrest of Mt. Saint Helens in 2004, the devastation of the December 26, 2004, Sumatra earthquake and resulting tsunami, the loss of life and destruction from the great Pakistan earthquake and associated landslides of 2005, and the chaos following Hurricane Katrina – demonstrate humankind's vulnerability to naturally occurring disasters. These events highlighted the costs associated with inadequate information and the consequences of inadequate planning for the dissemination of available or obtainable information. Slower ongoing changes— depletion of resources, degradation of soils, sea level rise, depletion and contamination of ground water— will also continue to produce serious consequences. It is possible to mitigate the impact of these events with carefully planned actions that have their foundations in science. Sustainable management of resources and hazards requires information that is costly, but less costly than inaction. Post-facto remediation can be prohibitively expensive.

Scientists, resource providers, policy makers and other stakeholders need an array of information to anticipate and mitigate natural hazards, ensure a steady supply of natural resources and energy, and develop appropriate international policies capable of sustaining life on Earth. Risks from hazards such as earthquakes, volcanoes, and other natural disasters have to be quantified and documented, and precursors or other early warning signals need to be detected. Long-term changes in Earth's surface chemistry and topography must be quantified to predict soil degradation and flooding. Demand for energy supplies drawn from the Earth will become an even more critical policy issue as worldwide competition for already scarce resources increases.

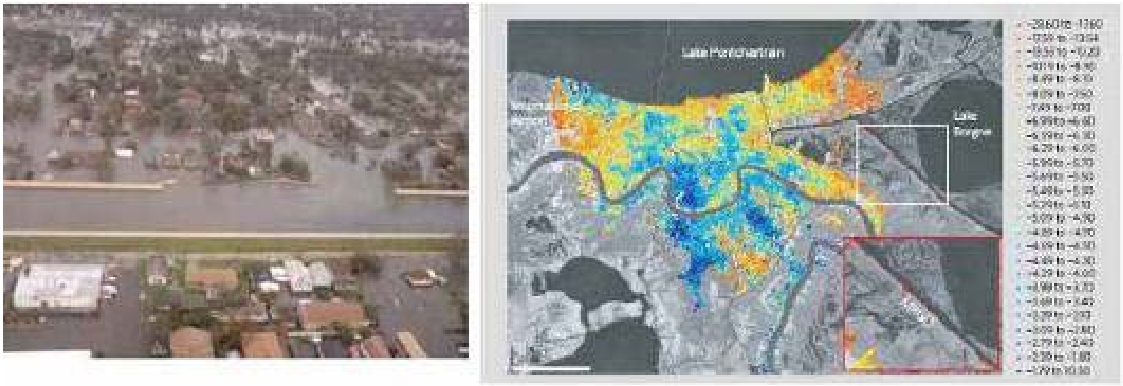


FIGURE 8.4. On the left is shown the breach in the New Orleans 17th Street canal levee which caused flooding in the city following Hurricane Katrina. (SOURCE: Marty Bahamonde/FEMA) On the right is a map derived from InSAR observations by the Canadian C-band RADARSAT satellite showing the rate of subsidence in millimeters per year for New Orleans and its vicinity in the three year interval preceding the hurricane (2002–2005). Insets show the location (white frame) and magnified view (red frame) of the region west of Lake Borgne, including eastern St Bernard Parish. Note the high rates of subsidence (> 20 mm/yr) on the levee bounding the MRGO canal, where large sections were breached when Hurricane Katrina struck. (Scale bar, 10 km). Note also that much of the map has no data due to lack of coherence in phase caused by vegetation – an L-band InSAR satellite such as is recommended here should provide better coherence. SOURCE: T. Dixon et al., 2006.

The necessity of developing a forward-looking United States energy policy will be one of the major political drivers for reorganizing priorities in Earth Sciences. The energy consumption per capita in Asia will grow in the next decade to at least European levels. This will require increased access to resources both for energy and mineral consumption. Easy access to hydrocarbons based on rudimentary scientific understanding of upper crustal processes is coming to an end. Hence, the energy producers must find new hydrocarbon resources and more efficiently produce from existing reservoirs. In addition, the need to exploit resources in hostile environments will continually increase. Future energy supply must be more diverse to meet global demand and the assessment of total resources will need to be much more accurate globally to maintain political stability. In the next 30 to 50 years, a transition to less dependence on hydrocarbons to fuel society will be technically possible, but any energy producing resource will have climate and environmental impacts. In addition, the demand on hydrocarbon resources will grow substantially in the next 2 to 3 decades in absolute terms, regardless of alternative energy policy priorities. A scientific basis will be required to estimate the impact on the biosphere of any given energy plan. (Note: Much of the Ecology panel's proposed program of missions will contribute substantially to assessing the environmental impacts of energy choices.) Currently, most studies of energy consumption and resource recovery are qualitative and the debate about exploitation of resources takes place without much scientific basis. Compare this situation, for example, to basic healthcare developments over the previous century and the related insurance policies that now help policy makers because they have a scientific basis. These political and global realities will drive innovation in Earth science over the next decades.

Development and implementation of appropriate policies at the national and international level will require a complete understanding of the fundamental nature of the Earth and how it evolves over time. In the past decade, remote sensing methods have greatly improved our understanding of the localization of strain in Earth's crust and how it drives catastrophic processes. It is critical that we are able to anticipate and understand these forces and their implied risks. Spaceborne data play a similarly critical role in mapping and monitoring resources such as oil, gas, and water, which are exploited now on a truly international scale—only global views from space will continue to enable sustainable policies.

These needs are encapsulated in the considerations of strategic roles that guide the observational requirements over the next decade (Box 8.1):

BOX 8.1 STRATEGIC ROLES AND QUESTIONS FOR SOLID-EARTH SCIENCE AND OBSERVATIONS

FORECASTING AND MITIGATING THE EFFECTS OF NATURAL HAZARDS: What observations can improve the reliability of hazard forecasts? What are the opportunities for early detection, ongoing observation and management of extreme events? What are the policy options to manage events that threaten human life and property? Can systems be managed to reduce their vulnerability before such events occur? How can useful information, including uncertainties, be communicated to decision-makers for the benefit of society?

DISCOVERING AND MANAGING RESOURCES: How can we improve our ability to locate resources that can be profitably produced? How can we improve our ability to produce known resources more safely and effectively? How can we limit potential environmental damage resulting from their exploitation? How can we monitor long-term changes in soil characteristics, land use and Earth surface topography to understand soil degradation and erosion in the context of climate change? How can information about surface chemistry be coupled to topographic information to yield predictive models for landslide activity?

ENABLING SCIENCE: What new observations, coupled with improved modeling capability, are most likely to advance our fundamental understanding of nature? How can this fundamental understanding be used to decrease hazards from natural disasters and to protect and improve our economy?

BACKGROUND ON OBSERVATIONAL NEEDS AND REQUIREMENTS

To provide the necessary information and tools to policy makers and other stakeholders, an Earth observation strategy is required to address the strategic needs described in the previous section. The panel's approach to develop this strategy, informed by previously-stated needs and goals from the scientific community (Solid Earth Sciences Working Group [SESWG], 2002), is focused on two primary themes (See Table 8.1): (1) Forecasting, assessment, and mitigation of natural hazards, and (2) Resource discovery and production.

Forecasting, Assessment, and Mitigation of Natural Hazards

Natural hazards pose an enormous threat to many parts of the United States and the world. In 2000, annual losses from earthquakes were estimated at $4.4 billion per year for the U.S. alone (FEMA circular 366). Volcanic eruptions destroy cities and towns, affect regional agriculture, and disrupt air travel. (In 1989, a KLM jet encountered a volcanic ash cloud from Redoubt Volcano near Anchorage Alaska and sustained >$80 million in damage). Flood hazards threaten civilian safety and commerce. The 1993 Mississippi River flooding caused $15-20 billion worth of damage and displaced 70,000 people; damage from the recent earthquake-spawned tsunamis in southeast Asia, which killed an estimated 270,000 people, will not be fully appreciated for some time. Additional long- and short-term hazards result from sea level change and landslides. Moreover, world population is rising most rapidly in areas of high risk from earthquakes, volcanoes, flooding, and landslides (e.g., Bilham, 1988; 2004).

TABLE 8.1 Key Questions to Identify Satellite Observation Priorities

Science Themes	Sub-themes	Key Questions
Forecasting, predictability, assessment, and mitigation of natural hazards	Earthquake forecasting	Where and how fast is seismogenic strain accumulating? How fast does crust stress change and how does this trigger earthquakes? Are earthquakes predictable? How do production of hydrocarbon reservoirs and injection of CO_2 into the crust trigger earthquakes?
	Volcanic eruption prediction	Can a worldwide volcanic eruption forecasting system be established using remote sensing data? What pre-eruption surface manifestations are amenable to remote measurement from orbit? What surface temperature change patterns are relevant? What can the measurement of emissions such as SO_2 and silicate ash tell us and what change patterns are relevant? How can multiple (topography, gas, temperature, vegetation) change patterns and measurements at craters be better interpreted for eruption forecasting? How often must a volcano be observed to provide a meaningful prediction?
	Landslide prediction	Which places show slowly moving landslides and how likely are they to fail catastrophically? Where are slopes over-steepened and lithologies vulnerable?
Resource discovery and production	Water resources	Where and when are groundwater reservoirs being depleted or recharged? Which critical aquifers are currently being driven into irreversible inelastic compaction? How does this affect future storage capabilities of the aquifers? Can surface hyperspectral and thermal measurements be coupled with measurements of surface deformation from InSAR to enable new concepts to detect and understand slow deformation processes related to fluid seepage phenomena?
	Petroleum and mineral resources	What fundamentally new concepts in surface geochemistry will allow for more comprehensive and precise surface geology characterization relevant for the hydrocarbon and mineral extraction industry? What are the changes in surface chemistry and thermal properties diagnostic of hydrocarbon and mineral resources? How can the efficiency of hydrocarbon and minerals production be improved? Using 3-D dynamic stress modeling at reservoir scales, is it possible to more accurately model stress dynamics and in particular predict failure processes at a basin scale?
	Terrains creating chemical risk	Can the risk of surface and ground water pollution from mineral and hydrocarbon waste sites be quantified from surface geochemical measurements? What are the key surface geochemical indicators detectable by remote sensing that are relevant to describing mining waste or landslide hazards? What are the detection limits at which soils containing natural health hazards such as asbestos, or swelling clays unsuitable for building construction, can be detected by hyperspectral imaging?
	Agricultural soil degradation	What is the true extent of the loss of topsoil due to poor management practices? Can remote sensing be used to measure carbon sequestration in agricultural soils? How well can we measure the leaching of nutrients and increasing salinization by remote sensing? Can remote sensing provide the kind of information needed for policy decisions by governmental entities world-wide? Will documenting the loss of prime agricultural soils force land use planners to assist in preserving our soil resource?

FIGURE 8.5 Earthquakes produce substantial economic and human loss which could be mitigated with better warnings. In the Northridge Earthquake, CA, of January 17, 1994, buildings, cars and personal property were all destroyed when the earthquake struck. Approximately 114,000 residential and commercial structures were damaged and 72 deaths were attributed to the earthquake. Damage costs were estimated at $44 billion (NRC, 1999). SOURCE: FEMA News Photo.

Assessing risk and developing successful policies to minimize loss of life and destruction of property requires precise measurements and powerful geophysical models. As an example, a recent FEMA report, "Impact of a Magnitude 7.0 Earthquake on the Hayward Fault: Estimates of Socio-Economic Losses Using HAZUS (Hazards U.S.)", states that economic losses associated with building damage from this earthquake scenario are estimated at nearly $37 billion (year 2000 dollars). Under a targeted rehabilitation program, major injuries and deaths could decrease by nearly 60%. If a comprehensive rehabilitation program were fully implemented, economic losses would be reduced by over 35% ($37 billion to $24 billion) and 1300 lives would be saved. Thus, better understanding of earthquake physics and the expected shaking from a given event will enable strategies such as building rehabilitation that can significantly reduce the risks to human life.

Natural disasters take their heaviest tolls in developing countries that do not have the resources for mitigation strategies. For example, the 1994 Northridge earthquake, although an economic disaster (Chapter 1), claimed only 72 unfortunate victims, in large part because much of the rupture plane lay beneath a sparsely populated mountainous area. Conversely, the comparably sized 1995 Kobe earthquake, which occurred beneath a densely populated area, claimed nearly 6,500 lives. The moderately larger 2001 Gujarat earthquake claimed 15,000 lives, 250 times the lives lost in the 1994 Northridge earthquake. These disparities reflect both the relative preparedness of these earthquake-prone zones and their population density. More accurate warnings of impending hazard can be used to avoid substantial suffering by focusing resources upon preparedness and disaster response.

Earthquake Forecasting

We know that stress transfer processes are important in triggering seismic activity. Current research is elucidating the nature of earthquake-to-earthquake interactions, rigorously quantifying the statistical likelihood of linkages, and elucidating time-dependent processes (e.g. postseismic relaxation, state/rate fault friction) that influence triggered activity. Emerging clues suggest longer-range interactions that are not fully understood. Such interactions are notoriously hard to identify and quantify: however, any such linkages should have detectable deformation signatures. Synoptic spaceborne imaging offers a new and promising means to identify deformation causes and effects linking regional earthquake events.

Identification of deformation events that are seismic precursors is the "Holy Grail" for earthquake research. Current earthquake hazard maps provide only coarse resolution of time and geography. Such maps depict the probability of exceeding a certain level of shaking over the next 30 to 100 years. The spatial resolution is typically on the order of tens to hundreds of kilometers. These maps are based on information about past earthquakes observed in the geological or historical record.

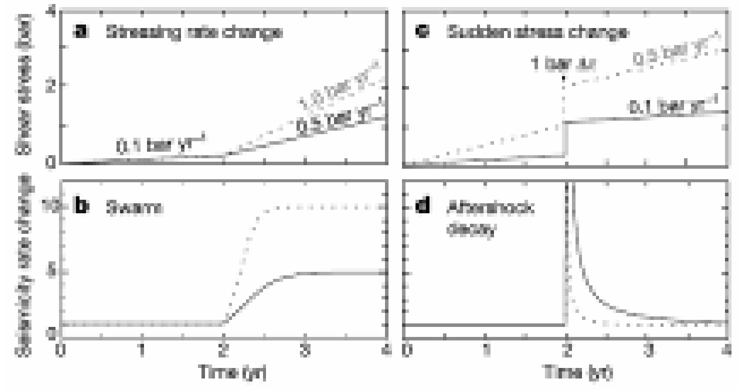
Future scientific studies of crustal deformation will yield insights into earthquake behavior, including answers to questions such as whether high strain rates indicate the initiation of failure on a fault or quiet release of stress, and how stress is transferred to other faults. These studies will drive the science that places more useful earthquake hazard maps into the hands of decision makers.

Forecasting Volcanic Eruptions

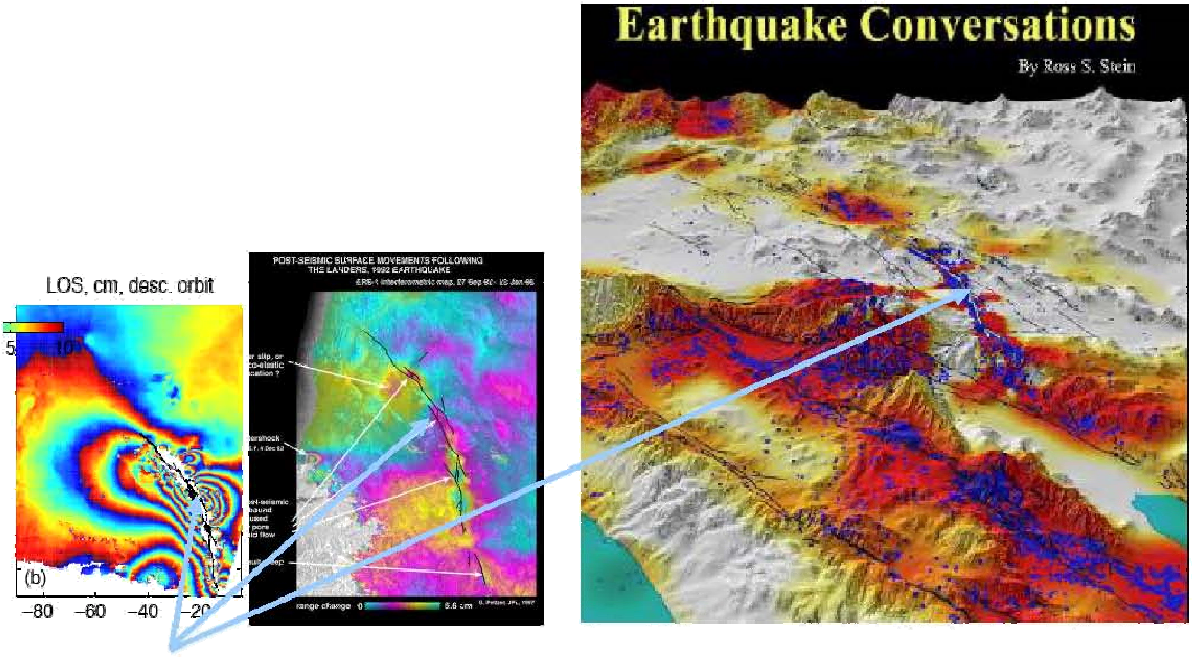
Volcanoes represent growing hazards to large local populations (Ewert and Harpel, 2004) and also present hazards to worldwide aviation passengers through engine dust ingestion (Salinas and Watt, 2004). At Pinatubo in 1991 a sustained increase in seismic energy and changes in the nature of seismic events were critical for successful eruption prediction (Harlow *et al*, 1996). However, only a small percentage of the world's volcanoes are instrumented sufficiently to facilitate predictions of eruptions from seismic data, and use of satellite-based remote sensing could provide crucial assistance in identifying regions where volcanic unrest is likely (Pritchard and Simons, 2002).

SIDEBAR 8.1 Relationship of Surface Deformation to Earthquake Probability

Recent developments in investigations of the mechanics of earthquakes have demonstrated that the frictional properties of faults, and, hence, their probability of rupturing depends strongly on the rates at which the faults are stressed. The fundamental concepts are illustrated in the figure below (from Toda et al, 2002). The top row shows example histories of shear stress in a region as a function of time; the bottom row shows the resulting rate of seismicity, which is directly proportional to the probability of an earthquake on a given fault segment. A change in stressing rate (left column) leads to an offset in the rate of seismicity. A sudden change in stress (right column) leads to an abrupt change in seismicity rate, followed by a relaxation back to the original rate.



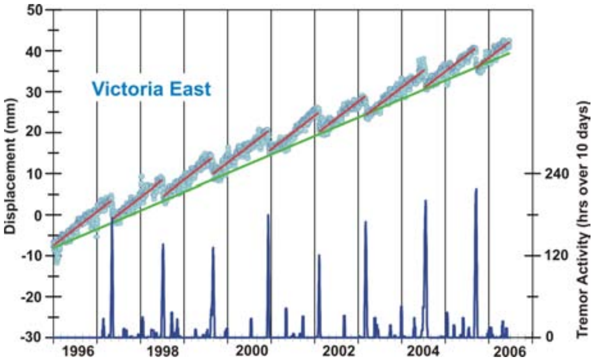
The stressing rate in a fault system such as that in southern California is the result of both loading from motions of the tectonic plates and loading from stresses generated by earthquakes within the fault system. Current investigations (e.g., Stein, 2003, right) infer this stressing rate from the observed rate of seismicity. Because the upper crust is elastic, a more accurate estimate of stress changes would come from observations of coseismic and postseismic strain changes estimated from InSAR measurements. SOURCES: Bottom-left panel, Fialko, 2004; Bottom-center panel, G. Peltzer, UCLA.



1992 Landers earthquake rupture

SIDEBAR 8.2 "Slow," or Aseismic Earthquakes

Faulting at subduction zones produces the world's largest earthquakes, characterized by the rapid release of strain over very large areas. Over the past two decades improvements in geodesy, or the precision at which we can measure crustal deformation, have made visible similar motions that occur over long periods rather than the almost instantaneous shock to the Earth we associate with earthquakes. These "slow" events, expressing themselves in waves with periods far too long to be easily measured by seismometers, redistribute strain throughout the crust and are important in determining the overall strain balance, and hence directly affect earthquake probabilities.



The Cascadia subduction zone in the U.S. northwest is a potential source of truly great earthquakes, perhaps as large as magnitude 9. Current GPS deformation measurements (top, above, from Melbourne and Webb, 2003) show interseismic deformations from ongoing tectonic motions. These motions reverse themselves for periods of 2-6 weeks every 14 or 15 months, as repeated slow earthquakes propagate across the area (see GPS measurements, bottom, courtesy H. Dragert). The vertical bars drawn on top of the GPS measurements represent known occurrences of slow earthquakes, and correspond to "abrupt" (week-long) changes in GPS station position. These events are most easily seen in deformation maps, and can greatly increase our ability to assess accurate strain accumulation information and lead to a better forecasting model. These slow earthquakes are not quite silent, and a unique non-earthquake seismic tremor signal has been detected accompanying them (Rogers and Dragert, 2003).

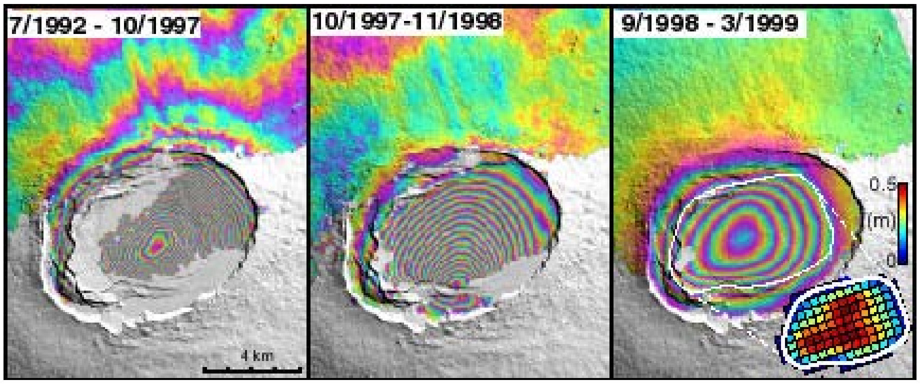


FIGURE 8.6 Monitoring of volcanic regions reveals unexpected phenomena, such as this series of interferograms from Sierra Negra in the Galapagos Islands. For most of the 1990s, inflation due to magma chamber growth dominated, but in the 1997-98 period a "trap-door" faulting episode shifted the deformation towards the caldera rim. Also shown as the inset is a map of the change in thickness of the magma reservoir estimated from the observed surface deformation. SOURCE: Amelung et al., 2000.

Significant progress toward unraveling the mechanics of magma transport from the source regions to the shallow crustal reservoirs in volcanoes has been made through field studies of ancient eroded volcanic systems, and through theoretical models. However, direct observational constraints on the style and dynamics of magma ascent are still lacking. Such constraints are crucial to forecast the replenishment and pressurization of shallow magma chambers that may potentially feed volcanic eruptions. Volcanic unrest episodes for any given magmatic system may be quite infrequent, and only a few volcanic systems around the world are closely monitored. Therefore, a global observation system capable of detecting the ongoing magmatic unrest will result in dramatic improvements of our understanding of volcanic activity and the associated societal hazards.

To improve hazard prediction for populated active volcanoes, we must determine the size and shape of magmatic reservoirs from geodetic, seismic, gravity, and other geophysical observations. We must also identify the type of magmatic unrest associated with eruptions, characterize detectable deformation prior to volcanic eruptions, and predict the volume and size of impending eruptive events. High quality geodetic observations are needed to constrain timescales and mechanisms of these processes.

Volcanoes are advantageous remote sensing targets because, unlike many natural hazards, their positions are well known: several hundred potentially active subaerial vents or craters are known today. Eruptions can therefore often be forecast based on observations from either the ground or space. Crater regions are affected by heat from magma and associated fluids and show detectable thermal changes (Harris et al, 2002). Gas emissions, especially SO_2, and volcanic ash are well known crater features linked to activity (Watson et al., 2004). Topographic changes (uplifts, slumps, landslides) are frequent. Vegetation in crater regions provides a sensitive barometer of all of the other changes. Because of this, many but not all eruptions may be forecast if changes in these observables are frequently sensed at fine spatial and spectral resolutions. Half of all eruptions may be preceded by detectable surficial changes with lead times of 30 days or more.

Currently, eruptions are monitored from orbit at coarse spatial resolution using MODIS on the EOS missions Terra and Aqua and with moderate resolution (90 m pixels) using ASTER on Terra (Patrick et al., 2005). Improving the spatial resolution and swath-width of an ASTER-like sensor would make it possible to detect changes earlier and could provide the foundation of a global eruption prediction system. A major initiative to improve volcano monitoring and eruption forecasting using surficial methods has been proposed by the USGS for U.S. volcanoes (Ewert et al., 2005). If implemented, this initiative would greatly expand ground truth data for a small subset of Earth's volcanoes. This is significant because it would greatly facilitate validation of the satellite techniques we propose, and could lead to an effective global volcanic eruption mitigation effort.

Forecasting Landslides

Landslides remain a threat to property and life in many parts of the world. Steep slopes, soil conditions and rainfall patterns are among the underlying causes of landslides. Thus, improved knowledge of topography (see Figure 8.3) and surface composition (Figure 8.2) are important for characterizing landslide risk.

Prediction of slow events is aided significantly by detailed observation of down-slope movements at the mm to cm level. Such observations can identify unstable patches of soil and have been correlated with landslide events (Hilley et al., 2004). Because these areas are relatively small and often heavily vegetated, conventional InSAR has not been an effective tool for mapping these small deformations. A new InSAR analysis technique, utilizing so-called "persistent scatterers," has been shown to yield high spatial resolution information including reliable mm-scale down-slope motions in terrains that challenge existing measurement systems. In this method individual points on the surface that do not suffer from radar "speckle" are isolated, and displacements at these points form a network that resolves the tiny motions over time. This method appears to be a reliable approach to finding areas prone to landslide, before any catastrophic collapse occurs.

Resource Discovery and Production

As world population increases, the demand for non-renewable resources grows. In particular the need for hydrocarbon resources will rise for the next few decades, as will the demand for other mineral resources. Rising demand will result in more vigorous exploration for new hydrocarbon- and mineral-bearing resources, as well as a higher level of production from known resources. At the same time, the need to reduce environmental impact during resource exploitation will increase. The petroleum industry is now developing methods to both detect and monitor hydrocarbon reservoirs remotely through a combination of airborne and spaceborne data.

Experiments exploiting hyperspectral data have allowed accurate and high resolution interpretations of subtle surface geological effects related, albeit indirectly, to mineral deposits and hydrocarbon reservoirs (van der Meer and de Jong, 2003). These activities require better data acquisition over larger bandwidths to understand fundamental geophysical and geochemical processes active in the upper layers of the crust. Indeed, the availability of high-resolution hyperspectral data will lead to comprehensive and precise surface geology characterization relevant for both resource exploitation and amelioration of environmental impact within the hydrocarbon and mineral extraction industry.

Management of hydrocarbon resources is facilitated by measurements of surface deformation and surface composition. Extraction of oil or gas from reservoirs leads to subsidence (e.g., Fielding et al., 1998) and occasionally triggers earthquakes (e.g., Segall et al., 1994). Quantitative interpretation of the deformation pattern can assist assessment of reservoir storage properties, as well as help guide an extraction strategy. Monitoring of deformation is also important in areas where ongoing subsidence from years of production results in significant subsidence in inhabited areas. In the U.S. such settling is problematic for communities around Houston, TX and Long Beach, CA.

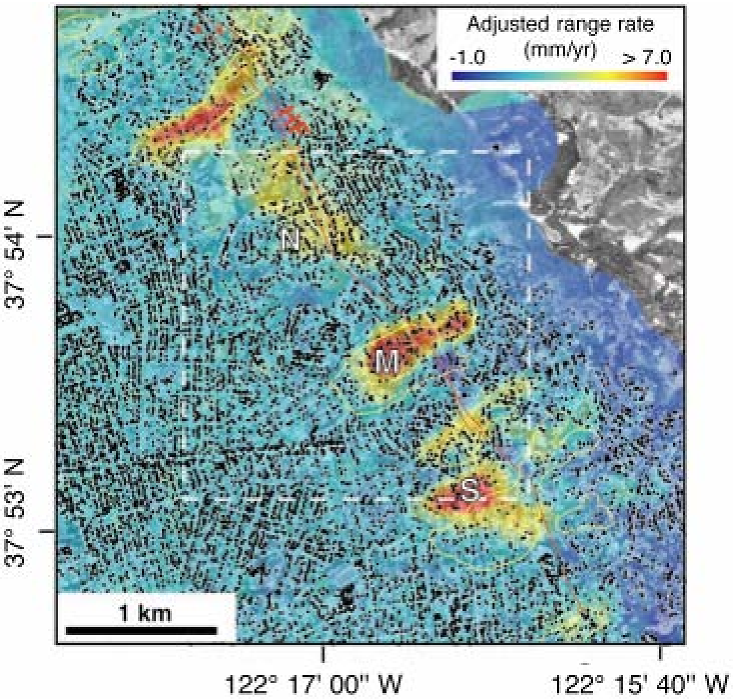


FIGURE 8.7 InSAR image acquired over the Berkeley Hills, CA, showing coherent down-slope motions that may be precursors of more rapid landslides. Increased down-slope movement in years with higher rainfall shows that potential hazard areas may be pinpointed in these high-resolution data and that hazard level may be assessed yearly. More rapid acquisition of images from the mission recommended here would allow assessment of the threat almost weekly. SOURCE: Hilley, et al., 2004).

Recent academic and industry research has shown accurate monitoring of surface deformation caused by fluid extraction can be directly related to the onset and evolution of micro-seismic events (magnitude < 2), occurring on natural faults and fractures in reservoir rock (e.g., Bourne et al., 2006). These observations are now being used to build subsurface models that may be used to predict accurately reservoir fluid flow dynamics as well as quantify the risk to well bore failure due to localized increased strain accumulations and fault re-activation. Well-bore failure is currently one of the most important hazards in the hydrocarbon fluid extraction process, leading to decreased production efficiency or to serious safety and or environmental hazards (Mayuga and Alen, 1970; De Rouffignac et al., 1995; Biegert et al.; Patzek and Silin, 2000).

Space-based monitoring techniques provide more comprehensive and more accurate surface deformation data than conventional geodetic techniques are able to achieve. The need for such techniques is increasing since the industry is now targeting large but ultra low-permeability reservoirs, which require application of major production enhancement techniques often involving the injection of (water) and steam to produce artificial fractures. This in principle leads to increased productivity, however, unless the injection process and the resulting localized strain increases can be monitored accurately, such operations can be highly ineffective and lead to significant damage to infrastructure costing on the order of $100M. In particular, the monitoring of sudden local compaction events are crucial to avoid costly well damage.

This development may have two profound consequences in future: on the one hand high resolution InSAR monitoring techniques may allow for efficient extraction procedures at acceptable environmental risks in remote (and often environmental sensitive) areas not possible with surface based techniques, except at (sometimes prohibitively) great cost and (unacceptably) large footprint. Secondly, the use of surface deformation and monitoring data for accurate 3-D geo-mechanical models of subsurface strain accumulations may provide an efficient way to study such dynamics at a larger but less controlled basin scale. Through application and up-scaling of new insights obtained recently in the hydrocarbon industries with respect to accurate 3-D dynamic stress modeling at reservoir scales (Bourne et al., 2006 and Maron et al., 2005), it will be possible to more accurately model stress dynamics and in particular predict failure processes at a basin scale. This enhanced ability could also lead to important new insights in earthquake prediction because there is typically much more information on the state of stress in reservoirs than typically available elsewhere.

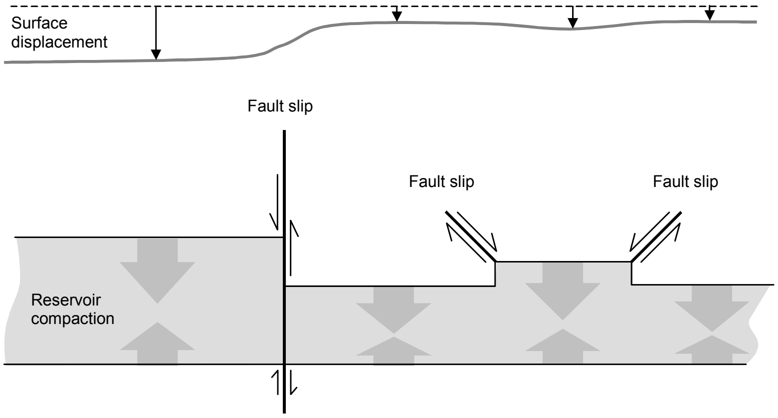
Injection of CO_2 into the crust is expected to become an increasingly important means for sequestering this greenhouse gas from the atmosphere. This fluid injection will lead to surface deformation. Monitoring this surface deformation will likely become an important technique for understanding reservoir behavior and monitoring integrity.

In addition, remediation of mine wastes is a costly undertaking and it has been shown that finely resolved remote sensing can provide valuable guidance in cleanup (Montero et al., 2005; Swayze et al., 2000). Current and historical mine waste dumps are sources of heavy metals, which under the right conditions can leach into surface and groundwater supplies to harm people as well as wildlife and vegetation.

SIDEBAR 8.3 Hydrocarbon production, surface deformation, and fault reactivation in the Yibal Field in Oman (Courtesy: Shell [Bourne et al., 2006]).

Obtaining observations in order to better manage production of hydrocarbons has substantial benefit in extracting precious resources. Typically only a fraction of the hydrocarbons stored within the reservoir rock are extracted, effectively wasting those left behind. In addition, deformation from compaction-induced internal deformation of reservoirs risks failure of the wells. The example shown here is from an oil field overlain by a gas reservoir, both producing from carbonate layers. Three types of data have been acquired to monitor the reservoirs: (i) microseismic, (ii) InSAR, and (iii) GPS. These data have the potential to image changes in reservoir fluid pressure, structure, and the resulting fault reactivation. As a result, geomechanical models can be built that enable accurate prediction of the risk for well-bore failure due to fault reactivation.

The schematic cross section shown below illustrates how a gas reservoir with rapid variations in thickness could cause fault reactivation as the result of depletion. Pressures decline uniformly throughout this reservoir, but compaction varies by up to 20% due to abrupt changes in reservoir thickness across major faults. These differences lead to stresses which could lead to failure of the faults and the accumulation of fault slip to accommodate these different rates of reservoir compaction.



Microseismic events located using a down-hole geophone array are shown below in cross section (left) and map view (center), where thick black lines denote fault traces interpreted at the depth of the oil reservoir. Most of the seismic activity is sandwiched between the gas and oil reservoirs. The field of surface displacement measured by InSAR over a 22 month period shows primarily subsidence due to reservoir compaction. (color range is +/-90 mm). In addition, a discontinuity in surface displacement is observed across the fault segment outlined by the ellipse. This suggests shallow aseismic motion on the fault coincident with the increased microseismic activity at depth.

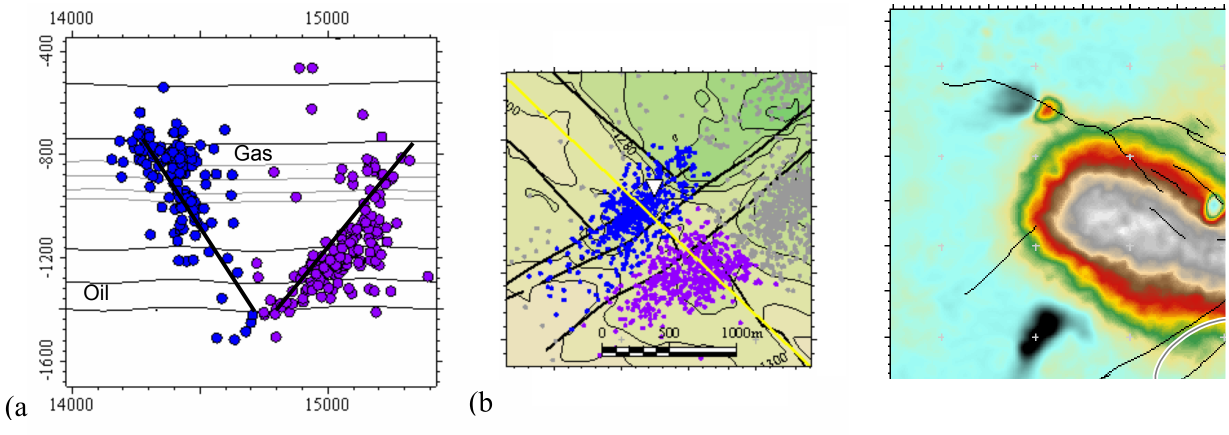


FIGURE 8.8 Cropland erosion processes driven by rain (left) and wind (right) after soil was tilled for planting in western Tennessee and central Indiana, respectively.

Another important natural resource that can be remotely monitored is agricultural soil. Agricultural soils around the globe are degrading rapidly by a variety of different mechanisms. Poor management practices and removal of crop residues for livestock feed and bedding cause loss of topsoil worldwide. Flooding results in the deposit of sediments and leaching of nutrients. Increased salinity due to poor irrigation practices or sea/ocean surge (caused by tsunami or hurricanes and urbanization) is permanently removing prime farm land from production (Lal et al., 2003). All of these changes can be detected and monitored globally by remote sensing of surface properties. Farmers and the public have not always worried about soil loss, as crop yields have increased despite these problems. The detrimental effects of soil erosion have been masked by increased applications of fertilizers, use of better crop varieties, denser plantings, more intense pest control, and more effective tillage and water management, as well as favorable weather. Nevertheless, in many countries, crop yields lag growing populations. Soil productivity losses are therefore often one of the main causes leading to the inability to provide adequate food supplies for some nations. In addition, the emerging emphasis on producing corn and soybeans for use as biofuels will cause farmers to bring more lands into production. Most of these new production lands are currently in hay or pasture that are on highly erodible lands and where tilling will result in increased soil erosion (since the soil is bare during critical high rain events in Spring when planting of corn and soybean crops occurs).

The existence of nonmarine life on Earth depends not only on soil fertility but also on the availability of fresh water. Human dependence on this latter resource is amply demonstrated during droughts around the world. Ground water, surface water, soil moisture, and snow pack all contribute to the global fresh water budget, and we need to understand how natural and anthropogenic processes redistribute water in both space and time.

Ground water currently provides 24% of the daily freshwater supply in the United States but remains a poorly characterized component of the terrestrial water budget. As drought conditions persist in the western U.S. and populations continue to grow, new ground-water development will exacerbate the national subsidence problems that cost $168 million annually and have led to coastal inundation and infrastructure damage.

The characterization of how the land surface above aquifers responds to ground-water pumping is very important in several ways. This characterization provides important insights on the subsurface controls of the aquifer system, the location of ground-water barriers and conduits, and the extent of the aquifer. When combined with ground-water level and pumping records, such characterization also provides critical hydrodynamic properties of the aquifer systems necessary to measure changes in the ground-water supply,

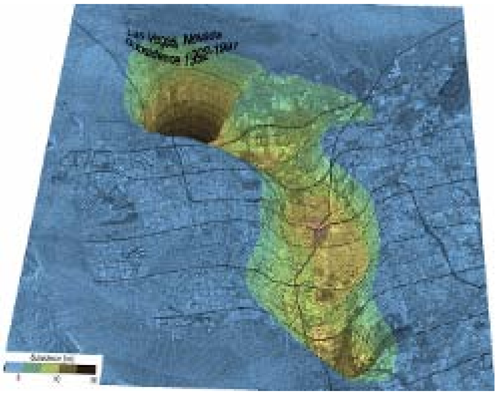


FIGURE 8.9 Many regions of the Earth are in motion, affecting the lives of millions of people; for example this subsidence near Las Vegas due to the withdrawal of groundwater. InSAR provides the only tool capable of mapping these changes globally. (Image from Amelung, et al., 1999.)

to model the aquifer system, and to constrain the terrestrial water budget. Deformation measurements with national coverage and routine imaging would significantly advance our ability to characterize both regional and continental scale aquifer systems. Moreover, deformation measurements could uniformly quantify our national aquifer system for the first time.

Natural and human-induced land-surface subsidence across the United States has affected more than 44,000 square kilometers in 45 states and is estimated to cost $168 million annually from flooding and structural damage, with the actual cost significantly higher due to unquantifiable ‘hidden costs’ [National Research Council, 1999]. More than 80 percent of the identified subsidence in the United States is a consequence of the increasing development of land and water resources, which threatens to exacerbate existing land subsidence problems and initiate new ones [Galloway et al., 1999].

Surface deformation associated with natural processes and human activity is observed but difficult to separate in geodetic network data. For example, sediment compaction, tectonic extension, sinkhole collapse, ground-water pumping, geothermal production, hydrocarbon production, CO_2 injection, and mineral extraction all produce both vertical and horizontal surface motion. By combining geodetic and hydrologic time-series data with spatially-dense deformation observations it is now possible to recognize and in some cases separate multiple land-surface deformation sources at a given location (e.g., Bawden et al., 2001). National coverage and routine imaging from space with high spatial resolution unachievable with a network of discrete surface stations would significantly advance our ability to understand the contributions of both human-induced and tectonic surface motions.

Summary of Data Needs

Requirements for identifying priorities of an observation system include substantial contribution to one or more of the Key Science Roles and Questions listed in Table 8.1. For each of the themes, ground-based measurements are already in use. However, the scope of coverage offered by satellite measurements would extend ground measurements to global scales and provide documented time histories of change. While intense land-based monitoring at a given site may yield insights for a given system, the recurrence interval for individual hazards is low and such monitoring will not yield the multiplicity of data needed for true advances in prediction. Global monitoring, allowing observations of many hazards over a short period of time due to the global frequency of events, will drive the improvements in prediction that decision makers need. Those measurements that will contribute most significantly are summarized in Table 8.2 along with the relevant sub-themes of Table 8.1.

HIGH PRIORITY MISSIONS

The mission recommendations presented here are based on a long and thoughtful planning process. The community engaged in research on solid-Earth hazards, resources, and dynamics has traditionally focused on NASA-sponsored observations of Earth using space-based techniques, e.g., the Crustal Dynamics Project (NASA, 1991). This community has carried out a series of planning exercises, starting with the Williamstown Report (Kaula, 1969). The most recent formal assessment of current capabilities and future needs culminated in the release of the SESWG Report (Solid Earth Sciences Working Group, 2002).

TABLE 8.2 Priority mission concepts

Brief Description of Mission	**Variables**	**Type of Sensor(s)**	**Coverage**	**Spatial Resolution**	**Frequency**	**Synergies with other panels**	**Related Planned or Integrated Missions (if any)**
Surface Deformation	Strain accumulation in seismogenic zones; Volcano monitoring; Stress changes and earthquake triggering; Hydrocarbon reservoir monitoring; Landslides; Solid Earth dynamics	InSAR	Global	50-75 m	~ weekly	Climate Ecosystems Water	DESDynI
Surface Composition and Thermal Properties	Volcano monitoring; Hydrocarbon exploration; Mineral exploration; Assessment of soil resources; Landslides; Solid Earth dynamics	Hyperspectral visible and near IR, Thermal IR	Global pointable	50-75 m	30 day, pointable to daily	Ecosystems Water	HyspIRI
High Resolution Topography	Landslides; Floods; Solid Earth dynamics	Imaging lidar	Global	5 m	Monthly to occasional	Ecosystems Water	LIST

In preparation for writing this report, the Solid Earth Hazards, Resources and Dynamics Panel considered the SESWG Report, the NRC review of the SESWG Report (Committee to Review NASA's Solid-Earth Science Strategy, NRC, 2004), as well as inputs from the RFI process (see Appendix XX) and from key presentations made by leaders in the community and within relevant federal agencies. The suggestions were evaluated based on their potential to transform the science; to promote societal applications; and on their risk, including degree of readiness and cost. Additionally, the panel considered whether the proposed measurements addressed international or national needs. Using this process, in addition to the requirement of maintenance of a robust geodetic network infrastructure, six measurement needs and conceptual missions were evaluated in some detail: (1) Measuring and monitoring surface deformation via InSAR; (2) Remote sensing of chemical and thermal properties of Earth's surface via hyperspectral and thermal imaging; (3) High-resolution (5 m) land topography via lidar; (4) Improved resolution of seafloor bathymetry via satellite altimetry; (5) Measuring and monitoring variations in Earth's gravity field via a GRACE-follow-on and gradiometry; and (6) Measuring and monitoring variations in Earth's magnetic field via satellite, balloon, and UAV observations.

The Panel deliberations enabled a prioritized list of mission concepts. The Panel agrees with the SESWG conclusion that a dedicated L-band InSAR mission is the highest priority mission for Solid Earth Hazards, Resources and Dynamics. The Panel goes beyond the SESWG report in prioritization of additional missions. The Panel also notes, as did the SESWG report, that a robust geodetic infrastructure is a prerequisite for a wide range of missions that depend on precise tracking: this infrastructure is needed by a broad range of communities both within and outside the solid-Earth community.

Mission to Monitor Deformation of Earth's Surface

Mission Summary – Surface Deformation	
Variables	Strain accumulation in seismogenic zones; Volcano monitoring; Stress changes and earthquake triggering; Hydrocarbon reservoir monitoring; Landslides; Solid Earth dynamics
Sensor(s)	InSAR
Orbit/Coverage	LEO, global
Panel Synergies	Climate, Ecosystems, Water

The science challenges related to observing surface deformation can be met through the use of repeat-pass Interferometric Synthetic Aperture Radar (InSAR) from an orbital platform. This mission would yield spatially continuous maps of ground displacements over wide areas, at fine resolution, and with sub-cm accuracy. The technical requirements for a radar mission capable of meeting these goals are: (1) L-band wavelength; (2) Approximate weekly repeat cycle; (3) Sensitivity at the mm-scale; (4) Tightly-controlled orbit to maximize usable InSAR pairs; and (5) Both left- and right-looking capability for 3-D vector displacement capability, rapid access, and more comprehensive coverage.

Some added objectives would be possible with the following technology enhancements: (1) ScanSAR operation for wide swaths; (2) Increased power and storage to operate 20% of the orbit on average; (3) Fully calibrated amplitude and phase data for polarimetry; (4) Multi-wavelength capabilities; C- and L-band imagery would provide the necessary control to map ice sheet dynamics; and (5) Along-track interferometry for ocean surfaces and other fast moving objects.

The InSAR mission recommended here would be a major technological advance over existing systems (Table 8.3). Existing systems were never designed to measure cm-level Earth deformations. InSAR would offer short repeat intervals for two important reasons. Short repeat intervals would resolve fine space-time details of deformation events. Short repeat intervals also allow multiple averaged acquisitions to lessen single acquisition noise caused by atmospheric propagation variations. Such noise limits the precision of current systems to cm or poorer accuracy in regions of even moderate humidity (Massonnet and Feigl, 1995; Goldstein, 1995; Zebker et al., 1997).

TABLE 8.3 Comparative Interferometric SAR Characteristics

Sensor characteristic	ALOS	ERS/EnviSAT	Radarsat	Desired InSAR
Signal to noise ratio	Moderate	Moderate	Moderate	High
Coverage	Good within station masks	Good within station masks	Few repeat pass areas	Global
Orbit control	Good	Moderate	Moderate	Excellent
Orbit knowledge	Excellent	Good	Moderate	Excellent
Atmospheric propagation effects	Poor	Poor	Poor	Good (can average many passes)
Ionospheric propagation effects	Poor	Good	Good	Very good (differential band correction)
Temporal correlation	Good (L band)	Poor (C band)	Poor (C band)	Good (L band)
Data availability	Moderate	Moderate	Costly	Excellent
Wide-swath for greater coverage	ScanSAR but no interferometry	ScanSAR but no interferometry	ScanSAR, no interferometry	Triple-width swath (experimental ScanSAR int.)

The use of L-band avoids much of the temporal decorrelation that plagues shorter wavelength systems (Zebker and Villasenor, 1992). Dual frequency observations allow correction for ionospheric propagation variations. A ScanSAR mode, designed to allow interferometric comparison of 330 km instead of 110 km swaths, could triple coverage on selected data acquisitions, so that either more frequent observations or more coverage could be obtained.

Data availability is another problem that limits the usefulness of the current generation of radar satellites. The principal bottlenecks are reliance on centralized receiving stations and processor facilities, and data policy. A new mission should address this issue by using a radically different, distributed ground system approach. Technological advances in communications, computers, and interferometric signal processing now allows the development of very low-cost receiving, processing, and distribution nodes which can then be networked together to form a worldwide data system.

To begin to understand earthquakes requires spatially distributed, vector measurements of surface displacement with absolute single component errors of 5 mm measured over 5 year intervals. This accuracy can be achieved by averaging multiple observations. Such vector measurements require observations from at least 3 look directions, which can be achieved by observation from both left and right sides during ascending and descending passes (4 look directions). For objectives related to ice deformation, deformation rates of 1 m/yr implies a displacement accuracy of 11 mm. This accuracy is easily achieved by averaging only a few interferograms. Volcanic studies require less accuracy but better temporal resolution. The single observation accuracy of 3-14 mm over length scales of 25-100 km is sufficient to meet our volcano-related objectives.

In summary, an InSAR mission can meet Earth deformation science objectives with a SAR system aboard a single dedicated spacecraft. The wavelength of operation should be L-Band with at least 80 MHz separation, providing ionospheric corrections similar to the L1/L2 GPS approach. Additionally, the orbit should be measured to better than a few cm accuracy with on-board GPS systems and should be maintained within a 250 m tube, guaranteeing that every image will be interferometrically valuable. In other words, with such instrumentation, interferograms documenting cm-scale changes will document regional and ongoing deformation. The side-looking antenna should point to either side of the orbit plane, ensuring the displacement measurements needed for such maps. The spacecraft should fly on a tightly controlled, exact repeat sun-synchronous polar orbit at an altitude of approximately 800 km to accommodate 3- and 8-day repeat periods. In this orbit the ground separation between orbit tracks is roughly 330 km at the equator. In the 8-day repeat phase, with an average radar swath of 110 km, steerable over a 330 km range, every point on the Earth will be imaged from one of three repeated orbits every eight days. Coverage of any specific area from an exactly repeated orbit will be provided every 24 days.

BOX 8.2 Earth Surface Deformation Mission

- New science: Global, fine-resolution map of strain accumulation, subsidence from water and hydrocarbon extraction, earthquake, volcano, and landslide natural hazards
- Applications: Earthquake risk assessment, volcanic hazards and prediction, human activity from resource extraction, sustainability of quality of life

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Mission to Observe Surface Composition and Thermal Properties

Mission Summary – Surface Composition and Thermal Properties	
Variables	Volcano monitoring; Hydrocarbon exploration; Mineral exploration; Assessment of soil resources; Landslides; Solid Earth dynamics
Sensor(s)	Hyperspectral visible and near IR, Thermal IR
Orbit/Coverage	LEO, global access
Panel Synergies	Ecosystems, Water

Many of the solid-Earth problems that can be addressed by remote sensing from Earth orbit fall into the category of environmental geology. The effects to be studied manifest themselves in change at the earth surface, and in particular over the upper micrometers that can be observed by remote sensing. The changes in surface geochemistry or surface temperature patterns provide clues to processes in the subsurface.

We define a mission consisting of two sensors that represent a considered compromise between requirements for measurement and feasibility of implementation at reasonable cost. Researchers sometimes express desires for spatial and spectral resolution as well as swath coverage and revisit times that are not compatible with technical feasibility, space-to-ground communication bandwidth or budgeted costs. Fortunately, the NRC RFI call produced many proposed missions that were well-conceived at realistic costs. With these realities in mind the following set of requirements was established to provide data/information to answer many of the questions stated above.

The core requirement is for a hyperspectral imaging sensor operating in the 400-2500 nm region. Many of the applications have been developed using airborne sensors such as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Green et al., 1998). Mapping of alteration minerals to show potential debris flow source areas on volcanoes (Crowley et al., 2003), asbestos in soils in California (Swayze et al., 2006), acidic mine waste (Swayze et al., 2000), swelling soils along the Front Range in Colorado (Chabrillat et al., 2002), agricultural soil properties (Ben-Dor, 2002), carbon in soils (Cozzolino and Moron, 2006) and mineral exploration (Gingerich et al., 2002) all have similar requirements for spectral and spatial resolution and signal-to-noise ratio. These studies could not have been accomplished with multispectral sensors.

One of the major challenges of imaging spectrometry is the high data rate resulting from the acquisition of images in hundreds of contiguous spectral bands. For this reason, at a spatial resolution of 30 m pixels and swath widths of 30 km or less have been proposed in the past. The only hyperspectral imager in earth orbit is Hyperion and its swath width is 7 km (Ungar et al., 2003). Given recent advances in detectors, optics and electronics, however, it is now feasible to acquire pushbroom images with 620 pixels cross-track and 210 spectral bands. Mouroulis et al. (2000) describe such an instrument design that allows

45 m pixels at nadir resulting in a 28 km swath. By employing 3 spectrometers with the same telescope, a 90 km swath results when the Earth's curvature is taken into account.

The hyperspectral system described above is exactly that being proposed for ecological studies by the Ecology Panel. Both require a pointable imager – for Solid Earth, to accommodate high-temporal resolution measurements of volcanoes for monitoring purposes. Given the high likelihood of short timeframe predictability for volcanic eruptions through crater-based monitoring, pointability of a sensor has great potential for saving lives and mitigating destruction in areas that are volcanically active.

For volcano monitoring and eruption prediction, experience has been gained using the ASTER instrument on the Terra spacecraft. ASTER is a multispectral sensor with, among others, 5 bands in the 8-12 μm thermal infrared region. Pieri and Abrams (2005) showed that it is possible to detect subtle changes in heat flow causing snow melt in the otherwise snow-covered slopes of the Chikurachki volcano on Paramushir Island, Russia prior to an eruption. The pixel size in the thermal channels is 90 m. The requirements for volcano eruption prediction are high thermal sensitivity, on the order of 0.1 K, and a pixel size of less than 90 m. An opto-mechanical scanner as opposed to a pushbroom scanner would provide a wide swath of as much as 400 km at the required sensitivity and pixel size. Placement of the thermal multispectral scanner together with the hyperspectral imager described above on the same platform would provide a new level of understanding of the problems discussed above and at the same time provide data for ecology and other disciplines.

BOX 8.3 Surface Composition And Thermal Properties Mission

- New science: Surface composition from maps of fine-resolution hyperspectral observations in optical and near-infrared, thermal emissivity and thermal inertia, mapping of gas release from processes at depth
- Applications: Volcanic hazards, resource exploitation and extraction, ecological drivers

8.4.3 Mission to Measure High-Resolution (5-m) Topography of the Land Surface

Mission Summary – High Resolution Topography	
Variables	Landslides; Floods; Solid Earth dynamics
Sensor(s)	Imaging lidar
Orbit/Coverage	LEO, global
Panel Synergies	Ecosystems, Water

The topography of the Earth's surface is a fundamental property that has relevance to all manner of physical processes. Meeting the science goals of high-resolution topographic studies requires mapping the global land surface on a 5 m grid, with decimeter vertical accuracy. The preferred technology to achieve these objectives is imaging lidar. (InSAR could also provide global mapping capabilities at somewhat lower precision, which would still represent a major improvement over what is currently available.)

Global topographic data are currently available at 30 to 90 meter resolution, with accuracy of several meters in the vertical. As Figure 8.3 illustrates, the proposed high-resolution topography mission would give Earth scientists literally a new view of the Earth's surface. At 30 to 90 meter resolution, many important topographic features are obscured, including many stream channels, floodplains, hillslopes, and landslide deposits. However, these same features are clearly visible at 5 m resolution, making it possible not only to map natural hazards, but also to detect changes in surface topography through time, and to better understand the processes that shape Earth's surface.

Lidar systems permit very precise (<10 cm height error) mapping from space. Lidar has already been used to globally map the surface of Mars (Smith et al., 1999, 2001), and will be used to map the Moon at even higher resolution than Mars in 2009. Interestingly, lidar has not yet been used to map Earth's continents, and we currently know the topography of Mars at far higher resolution that we know it for Earth!.

While earlier-generation spaceborne laser systems (e.g., the Shuttle Laser Altimeters; Garvin et al., 1998) were generally single-beam systems that collected profiles of the surface along the spacecraft ground track, emerging technology will enable spatial elevation mapping. Three approaches could enable spatial mapping of Earth's surface from an orbital platform. The first uses a single laser beam and a scanning mechanism to spatially map the surface, as demonstrated by the GSFC airborne Laser Vegetation Imaging Sensor (LVIS; Blair et al., 2001). Analysis indicates that kilohertz-ranging rates could be achieved from an orbital scanning system (Degnan, 2002). The second approach takes a single laser and splits the beam in numerous parts via a diffractive optical element; separate detectors are used to measure elevation in each backscattered beam. This approach is being implemented in the design of the Lunar Obiter Laser Altimeter (Smith et al., 2006), to be flown on the Lunar Reconnaissance Orbiter to be launched in 2008.

The third approach uses a single laser beam to illuminate a broad swatch of surface and a pixilated detector in which each pixel makes a time of flight measurement. An example that uses this approach is the Lincoln Laboratory JIGSAW airborne system (Heinrichs et al., 2001), and analysis has shown that 5 m mapping of the Moon could be achieved in two years using an adaptation of this system (Zuber et al., 2004). Study will be required to determine the optimal technological approach for the high-resolution topographic mapping mission. In any case, megabit to gigabit data rates will need to be managed during mapping operations.

Cloud cover will limit the coverage available from each individual pass, so multiple passes will be required for complete coverage. A relatively long mission lifetime may be needed to achieve the desired spatial density and coverage, and repeated measurements over several years would facilitate detecting surface changes such as topsoil losses to erosion.

Lidar measurements can be corrected for many vegetation effects, as the full range profile at each post can be recorded. Thus the structure of the vegetation canopy can also be mapped at high spatial resolution, along with the underlying topography, which would provide an improvement over the sparser sampling that would be obtained earlier in the decade by the DESDynI mission. Since the height precision of lidar is unsurpassed, it is the preferred method for a topographic mission. However, the mission is not intended to be flown until late in the decade, allowing time to invest in technology development before a final selection must be made.

InSAR has been used for both local (TOPSAR, GEOSAR) and global (SRTM) topographic mapping, and is capable of retrieving elevation data from precise parallax measurements using two radar antennas. While the highest precision results from systems with two antennas on one platform, repeat pass orbit geometries have realized 5 m height accuracy (Zebker et al., 1994). The Shuttle Radar Topography Mapping Mission (SRTM) used two antennas simultaneously to minimize atmospheric propagation effects and mapped the Earth at arcsecond (30 m) posting. The German space agency DLR plans to acquire global topography with 12 m posting and 2 m vertical precision via the tandem X-band InSAR (TanDEM-X), scheduled for launch in 2009. For the high-precision topographic mission, the posting and vertical precision could be improved to 5 m and 1 m, respectively, using a dual-antenna system or two contemporaneous satellites flying in tandem. Multiple passes of a single-antenna system could provide areal coverage in regions not subject to limiting temporal decorrelation. The Panel recommends the pursuing the lidar mission because of its greater accuracy and complementary use for improving measurements of ecosystem structure, but data from TanDEM-X would allow important progress to be made before the lidar mission is flown later in the decade.

BOX 8.4 High-resolution Topography Mission

- New science: High-resolution, high-precision topographic data, in most cases with vegetation effects quantified and removed.
- Applications: Geomorphology, landslide hazards, flooding, hydrology, ecology

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Mission to Monitor Temporal Variations in Earth's Gravity Field

Mission Summary – Temporal Variations in Earth's Gravity Field	
Variables	Ground water storage; Glacier mass balance; Ocean mass distribution; signals from post-glacial rebound, great earthquakes
Sensor(s)	Microwave or laser ranging
Orbit	LEO, global
Panel Synergies	Climate, Water

The problem of temporal variations in Earth's gravity field is inherently interdisciplinary. The largest variations on time-scales of months to decades are associated with the water cycle (see Chapter 11). Changes in ocean circulation also result in mass variations that are associated with changes in the gravity field. In this section we focus on how observations of temporal changes in Earth's gravity provide important information about Solid Earth dynamics.

The largest signal from Solid Earth processes is the variation associated with postglacial rebound, which leads to substantial secular increases in the gravity field over formerly glaciated regions including the region surrounding Hudson Bay in Canada, Scandinavia, Antarctica, and Greenland. The pattern and amplitude of predicted secular changes in gravity are sensitive both to Earth's radial and lateral variations in viscosity and to the details of the ice load history. Combining observations of changes in gravity with observations of deformation of Earth's surface improves our ability to constrain models and to separate changes in gravity caused by postglacial rebound from changes caused by ongoing redistribution of water and ice mass.

Great earthquakes cause large redistributions in mass that cause observable changes in Earth's gravity field. Monitoring the postseismic relaxation of these mass changes would provide unique information about Earth's viscosity structure in subduction zone regions and make valuable contributions to our understanding of the variation of stress with time.

Even time-varying processes associated with the generation of the geodynamo in the fluid core result in variations in the gravity field. These include elastic deformation of the overlying mantle and crust associated with dynamic pressure variations at the core-mantle boundary and rotation of the asperical inner core caused by torques from the geodynamo. Although these signals are weaker than those from redistribution of water mass at Earth's surface, they can be recognized because they have distinct spatial patterns.

The Gravity Recovery and Climate Experiment (GRACE), a collaboration between NASA and the German space agency to monitor temporal variations in Earth's gravity field, was launched in 2002 with a mission life now estimated as nine years. Already signals from postglacial rebound beneath Hudson Bay are visible. However, regions of ongoing postglacial rebound are typically regions where variations in ice mass and water storage are also substantial, so the solid-Earth and hydrologic signals are mixed together. In order to separate these two signals, a multi-decade period of observation is required, which requires a follow-on mission to GRACE. Any gap in coverage between GRACE and GRACE-II will disrupt the time series of observations, complicating its interpretation.

The change in gravity from the great 2004 Sumatra earthquake has also been observed by GRACE. Monitoring the temporal variation of this feature is crucial. It is also important to improve the spatial resolution of the measurements of the time-varying gravity field. For each improvement in spatial resolution by a factor of three, an order of magnitude more earthquakes will be observable.

BOX 8.5 Temporal Variations in Earth's Gravity Field Mission

- New science: Separation of time varying gravity signal from postglacial rebound from changes caused by ongoing redistribution of water and ice mass; monitoring postseismic relaxation
- Applications: Geodynamic studies, improved estimates of tide gauge motions

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Mission to Measure Oceanic Bathymetry

Mission Summary – Oceanic Bathymetry	
Variables	Seafloor topography
Sensor(s)	Altimeter (nadir or swath)
Orbit	LEO, global
Panel Synergies	Climate, Ecosystems, Health, Weather

Variations in the pull of gravity caused by seafloor topography cause slight tilts in ocean surface height, measurable by satellite altimeters. Estimates of seafloor topography from previous altimetric missions have led to spectacular global bathymetric maps with spatial resolution down to ~ 12 km (e.g., Smith and Sandwell, 1997). These altimetric missions have had nadir-pointing radars flown in repeat orbits and the spatial scale has been limited by the distance between orbits. Higher resolution measurements could be obtained by flying a nadir-pointing altimeter in a non-repeating orbit or by swath altimetry, as in the SWOT mission discussed by the Water Panel in Chapter 11.

Doubling the spatial resolution of our knowledge of seafloor topography would improve our understanding of the geologic processes responsible for ocean floor features including abyssal hills, seamounts, microplates, and propagating rifts. It would improve tsunami hazard forecast accuracy by mapping the near-field ocean topography that steers tsunami wave energy. Determining the distribution of seafloor roughness would improve models of ocean circulation and mixing. Bathymetric maps have numerous other practical applications, including navigation (On January 8, 2005, a billion dollar U.S. nuclear submarine ran at full speed into an uncharted seamount.) reconnaissance for submarine cable and pipeline routes, improving tide models, and assessing potential territorial claims to the seabed under the United Nations Convention on the Law of the Sea.

BOX 8.5 Ocean Bathymetry Mission

- New science: Geologic processes responsible for ocean floor features, distribution of seafloor roughness
- Applications: Tsunami hazard forecasts, ocean circulation, navigation

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Monitoring the Geomagnetic Field

Understanding the origin of Earth's magnetic field was ranked by Albert Einstein as among the three most important unsolved problems in physics. While we now know that the magnetic field is generated in the convecting metallic outer core, where self-generating dynamo action maintains the field against decay, the detailed physics by which the dynamo operates is not well understood. We do not know how much longer the current rate of decay of the dipole field, sufficient to eliminate the dipole field in 2000 years, will go on. This is of more than academic interest since it is the magnetic dipole field that shelters our planet from bombardment by charged particles from space. On shorter time scales, the ongoing dipole decay is connected to the South Atlantic Magnetic Anomaly where the field at Earth's surface is now about 35% weaker than average. This "hole" in the field impacts the radiation dosage experienced by satellites in low-Earth orbit.

Advances in understanding the geodynamo rely on global observations of the geomagnetic field and its temporal changes to constrain ever-more-sophisticated numerical models of magnetohydrodynamics. In recognition of the importance of this rapidly-advancing scientific discipline, the SESWG Report (2002) recommended improved access to and analysis of existing observations, as well as flying constellations of satellites in varying orbits in order to better determine future changes in the global magnetic field. The NRC review of the SESWG Report (NRC, 2004) strongly supported these recommendations and noted that the SWARM Mission (http://www.esa.int/esaLP/LPswarm.html) planned for launch by the European Space Agency in 2009 would largely satisfy the SESWG goals.

The Solid Earth Panel concurs that this field is in the strong position of having the acquisition of important satellite data already committed to by international collaborators. It is important for NASA to make significant contributions to these missions, as well as to ensure that U.S. scientists have access to the data. Later in the decade it will be important to reassess the situation and plan future missions.

OTHER SPECIAL ISSUES

In this section we describe additional observing priorities that NASA should consider. These support the main science objectives discussed above, but with non-spaceborne technology. We have previously addressed the maintenance of the terrestrial reference frame, so here we concentrate on suborbital platforms, international collaborations, and policy issues.

The Role of Suborbital Remote Sensing

Many problems in Earth science require global data, however certain significant issues require higher spatial and/or temporal resolution in a specific region. Many applications could benefit from tactical deployment of manned or unmanned aerial platforms and instruments. Examples include rapid-repeat deformation of active volcanoes using InSAR, IR, and hyperspectral measurements, observation of postseismic deformation from recent earthquakes, or transient events from localized floods, landslides, or other disasters. All of these augment and localize the synoptic work described above, extending the science objectives listed previously.

The solid-Earth panel recommends that NASA develop technologies implemented on operational airborne platforms to augment the space program. In particular, repeat pass InSAR on a UAV with real-time interferogram generation would be invaluable for directed study of rapidly changing surfaces. Rapid deformation before or after earthquakes or during volcanic eruptions could be analyzed sub-orbitally at time scales not easily sampled using spacecraft.

Stratospheric Mission Concepts

One area where revolutionary concepts are desired is stratospheric platforms from which *in situ* and remote Earth science measurements can be made. NASA contracted Global Aerospace Corporation to lead a small study to evaluate the capabilities of the candidate platforms to meet NASA Earth Science objectives. The science areas where these platforms are expected to make significant impact include

Atmospheric Chemistry, Earth Radiation Balance, and Geomagnetism. Potential platforms include Ultra-Long Duration Balloons (ULDBs), other balloon concepts, airships, Uninhabited Air Vehicles (UAVs), and crewed aircraft. Of these ULDB's are by far the most affordable.

Individual stratospheric balloon platforms, built in quantity, are estimated to be less than 1% of the cost of a satellite. A constellation of 100 could therefore give synoptic coverage for the cost of a single space satellite. Using such approaches, instrumentation can be recovered in order to allow post-flight verification. As technology advances, balloon platforms therefore offer easy upgrade through recovery and re-launch of payloads. The cost of a single guided balloon mission configured for the Crustal Magnetic Field Measurement Mission is estimated at about $3M, not including advanced technology development, for a 100-day flight after the appropriate technology is developed (see Section 4). Since this mission cannot be accomplished by current space satellites or other current stratospheric platform technologies, its cost to benefit ratio is very high.

Sub-orbital magnetic studies hold particular promise for answering a number of interesting questions including (1) What are the natures of the upper, middle, and lower crust? (2) How is the South Atlantic magnetic anomaly changing? (3) What is the sub-ice circulation in Polar Regions? (4) What are the stratospheric/atmospheric processes with magnetic signatures? (see, for example, http://core2.gsfc.nasa.gov/research/mag_field/purucker/huang/RASC_WorkshopReport_final.pdf.) Obviously, these questions overlap with questions in Climate Science as well as Environmental Sciences related to Space weather phenomena.

There are two reasons why sub-orbital observations are relevant for studying these questions. First, data recorded at stratospheric altitudes would fill an important gap in bandwidth which cannot be filled by compiling measurements from satellite platforms or from airborne platforms. At stratospheric altitudes, processes in the crust can be directly measured. Second, stratospheric missions, for example ULDBs, are low-cost relative to satellite missions, and could provide efficient and wide-ranging observations over a relatively short period of time.

The advantages of using "stratospheric satellites" are that observations at stratospheric altitudes allow the separation of various components of Earth's magnetic field. In addition such observations allow for the inclusion of intermediate spatial wavelength information to existing surface and satellite surveys. Stratospheric platforms can enable long term coverage over hard to access sites and provide space weather event warnings for polar satellites.

International Collaborations

Radar Observations: A number of our international colleagues have developed spaceborne radar sensors over the past decade, including the European Space Agency (ESA) with the ERS and Envisat satellites, Canada with its RADARSAT satellite, and Japan with the ALOS system (see addendum to this chapter, "International Cooperation: The Case for a U.S. InSAR"). These are mainly short-wavelength radars emphasizing radar imaging rather than the deformation capability of InSAR. Although these satellites provide important information on an "as available" basis, there are three serious problems: 1) the short-wavelength radars rapidly lose phase coherence over vegetated areas, so their applicability is limited mainly to arid regions; 2) the short-wavelength sensors do not provide useful constraints on ecosystem structure; and 3) there are many conflicting demands for scheduling observations, so acquisitions of images for the science described in this chapter are severely limited. As our partner agencies have invested in short-wavelength radars, it remains for us to develop the technically more challenging long-wavelength sensors that better maintain phase coherence and are also useful for obtaining ecosystem structure. By flying our sensors coincident with the international platforms, the maximum science return can be obtained by covering the microwave spectrum.

Magnetic Field Observations: Observations of spatial and temporal variations in Earth's magnetic field will be dominated in the next decade by international missions such as SWARM. It is crucial for NASA to facilitate participation and access to the data for U.S. scientists.

End-To-End Systems for Integrating Observations in Management Decisions

It is also imperative that any technological advance be tightly integrated with a policy infrastructure so that the science return can be adequately incorporated in important decisions, whether they are for hazard mitigation, national security, or for the sustenance of life on Earth. Only informed policies are viable in the long run, and the science proposed here is critical to correct public decision processes. However, simply making the observations and measurements is not enough to answer these questions. If we are going to fully reap the rewards and benefits of an integrated and focused system of Earth observations, we need to also make comparable investments in an integrated analysis of the data--across disciplines, across missions, and across other space programs.

In Situ Observations

These spaceborne data provide the global synoptic view of the processes studied, yet many projects require significant input from field observations. We recommend a strong field component for any of the science presented here to provide information unavailable or difficult to obtain from space. Seismic networks, continuous GPS networks to provide sampling of higher frequency deformation, and ground-based measurements of soil erosion are notable examples.

Finally, as emphasized in the Overview, high precision global networks of the Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR), provide the foundation for virtually all space-based and ground-based observations in Earth. The terrestrial reference frame is realized through integration of these observing systems. It is through this reference frame that all measurements can be inter-related for robust, long-term monitoring of global change. A precise reference frame is also essential to interplanetary navigation and diverse national strategic needs.

Synergistic Observations from Other Panels

Spatially-dense crustal deformation measurements are the primary data need recognized by the Solid-Earth panel. Acquisition of these data is also a priority of the Climate and Ecosystem panels, specifically for the observation of ice flow in the polar ice sheets and for characterization of vegetation canopy structure and biomass, respectively. All three panels have endorsed a conceptual baseline mission that operates at wavelengths from 6-24 cm, with 24 cm the preferred wavelength for natural hazards applications in the solid-Earth area. Instrumental augmentations and refinement of the parameters will add appreciably to the utility of InSAR in the Climate and Ecosystems areas.

The Climate panel requires InSAR data for observation of ice sheet flow and dynamics, specifically to address the role of glaciers and ice sheets in sea level rise and possible changes in Earth's climate. These data map ice velocity and discharge by ice streams and glaciers worldwide and quantify their contributions to sea level rise. InSAR data will help characterize the temporal variability in ice flow well enough to separate short-term fluctuations from long-term change. InSAR will also identify fundamental forcings and feedbacks on ice stream and glacier flow to improve the predictive capability of ice-sheet models.

While most research to date has been carried out at a shorter, 6 cm wavelength (C-band), theoretical models show that the ice objectives can be met using the 24 cm wavelength preferred by the solid-Earth community. The longer wavelength will penetrate 100 m or more into dry snow so that the measured signal is from a deeper region than the 20 m depth usually seen at 6 cm. Multiple frequencies would allow profiling of the ice motion and structure with depth. Hence one possible improvement is the inclusion of a second frequency on the radar platform. This results in a more capable and versatile instrument, albeit at a cost in complexity and budget.

For the Ecosystem panel, one major uncertainty is the 3-dimensional structure of vegetation on Earth's terrestrial surface, and how it influences habitat, agricultural and timber resources, fire behavior, and economic value. InSAR is one valuable tool to characterize structure, as the waves that penetrate the canopy have a different phase in the radar echo than those reflected off the top of the canopy. These differences are even more apparent if the polarization of the reflected signal is recorded.

In the case of vegetation studies, the longer wavelength of 24 cm is preferred as it penetrates deeper into the canopy and the return does not saturate at low biomass values. However, the desire to separate scattering mechanisms by polarization makes a polarimetric addition to the instrument desirable for ecosystem research. While many objectives can be met with the single polarization instrument proposed by the solid-Earth panel, a polarimetric instrument would return more scientific benefit.

All of the above are advantages resulting from multiple use of the InSAR measurements. Potential scheduling conflicts could arise, however, from multiple requests for the instrument at the same time. All three of the panels above can be satisfied with the 1-2 week return orbit, so this is not likely to be a planning problem. We do not foresee a significant conflict in operation either, as the geographical regions of most interest to the communities are largely disjoint. The ice community requires acquisitions over Greenland and Antarctica. The solid-Earth scientists need data acquired over active tectonic areas, mainly the Pacific rim, and the Alpine-Himalaya belt. Major forests are located in tropical Asia, Africa, and South America—some overlap occurs in the southwestern Pacific region with seismic and volcanic activity. As volcanoes often are located in areas of ecological interest, coordination in radar modes and frequency of coverage will have to be addressed for these sites.

SUMMARY

Sustaining quality of life necessitates a thorough understanding of the physical and chemical processes that shape the Earth. Cooperating with natural processes and planning for hazards and other catastrophes prudently will minimize loss of life and property. Successful exploitation and discovery of energy and mineral resources will become an increasing challenge over time. Thus, we must recognize the critical need to understand, assess, and predict catastrophic events such as earthquakes, volcanoes, and floods, as well as to continue our ability to mine energy and other natural resources from the Earth. We must make detailed and accurate measurements of the surface in order to analyze and manage the Earth and the fragile water and soil resources that sustain life. Recognizing that hazardous events happen at any one locality infrequently, we acknowledge the need for a global observational capacity.

We have identified three space missions as crucial. First, we recommend an InSAR mission to characterize globally deformation of the Earth's crust. Second, we propose a hyperspectral optical and near IR mission to observe and record surface composition and thermal properties. Third, we advocate a mission to precisely measure land surface topography. Missions to determine long-term variations in Earth's gravity field, to determine ocean bathymetry with improved spatial resolution, and to observe the spatial and temporal variations in the geomagnetic field are also important. Improvements in and continued operation of the global tracking network are crucial for the success of all satellite missions. We also recommend that suborbital and field programs continue to play a vital role in managing our Earth. These supporting measurements and analyses are needed for the development of viable national and international policies and for informed public decisions. The missions we propose will be valuable not only to solid-Earth science but to several other communities as well. The ecology, hydrology, and climate panels in particular will find significant benefit in all three of our highest priority missions.

ADDENDUM: International Cooperation: The Case for a U.S. InSAR

Many nations are pursuing spaceborne radar programs. However, for a variety of reasons, it is at best uncertain if these programs can return the quantity and kind of data required to meet the science objectives discussed in this report. Many of these systems exist only as concept studies, and are no more "real" than the ongoing radar studies that NASA has sponsored over the past decade. Below, the committee assesses briefly the usefulness of several of these systems to perform the crustal deformation-, climate-, ecological-, and commercial-related applications that it thinks the nation should undertake:

1. ALOS. This L-band satellite, listed in Table 8.3, was launched by Japan in early 2006 and is currently operating. The data quality appears high and after some trouble controlling the orbit, is now delivering test data to the calibration/validation team. ALOS, in a 41 day repeat cycle, will image much of east Asia several times per year. However, it will not image the U.S. swaths more than once or twice per year over its five year lifetime due to data rate constraints.

   An interagency working group is trying to offer NASA data relay capabilities to JAXA to increase coverage over the United States, but it has not yet succeeded. Thus, while these data can yield some engineering studies for L-band SAR, the temporal density is an order of magnitude too sparse for eliminating atmospheric interference or to give insight into transient phenomena. This satellite will be finished long before a new satellite can be launched by the U.S. in any case, so it is at best a stop-gap engineering mission.
2. China and the HJ-1 satellites. China has an ambitious plan to orbit up to 10 radar satellites (4 of which form the HJ-1 series) over the next 10-15 years. There are reports by word of mouth that the first satellite was launched last April but this is not substantiated via existing web-reachable documents. This is reputed to have been an L-band system, and the orbit, repeat cycle, and capabilities of the sensor are not widely known. The published reports state that the next two satellites to be launched will be a pair of S-band radars in 2007; these are possibly nearly as effective as L-band for reducing decorrelation. However, we believe that it is unlikely that enough data will be made available to the U.S. science community to address our science objectives, and in any case we do not see how there will be sufficient participation by U.S. scientists to define the proper orbits and coverage to begin to meet our own needs. If U.S.-Chinese relations change drastically, and NASA agrees to support the Chinese space program significantly, then of course these satellites could be useful.
3. Arkon-2: Arkon-2 is a military system with three radar frequencies, and as far as we know no U.S. scientists have been asked to join a Russian team to plan for scientific use of the sensor. It is possible that the Russians could decide to place this radar in an orbit useful for scientific radar remote sensing investigations rather than a militarily useful orbit, and then sell the data commercially. If that it the case then we could consider a make/buy decision on data. Past experience has been that Russian radar data products do not satisfy the science community's needs as regards to data volume, satellite tasking, orbit geometries, and, most importantly, data quality.
4. MAPSAR: MAPSAR is a Brazilian radar designed for equatorial coverage of the Amazon region. Even if the capacity of the sensor could be increased and U.S. scientists could command the satellite to acquire data for our use, the conflicts regarding orbit configuration and data allocations are formidable if we wish to use the same satellite for the polar regions as well as the Amazon. As this is Brazil's first imaging radar satellite system, we cannot assess whether it will be capable of delivering the amount, type, and quality of data needed to solve our hazards, environmental, climatic, and commercial needs.
5. Sentinel-1: This ESA system is based on a C-band radar; therefore, it cannot address science needs that require a long wavelength system. The Europeans have a long history with SAR and will probably build a very capable instrument, but this committee recommends that the United States have access to a longer wavelength system to enable the important next steps described in this report (see chapter 8). The nation has benefited from using ESA radars over the last 15 years and will continue to benefit from them in the future; however, a change in technology is needed for the real breakthroughs. The committee is

aware of discussions regarding future Sentinel radars being operated at L-band or the even longer P-band; however, these are but concept studies (equivalent to what NASA would term, "Phase A" studies) and not real systems we can use. We note that a commitment by NASA towards a real ESA partnership has the potential for substantive cost savings.

6. Other systems: RADARSAT-2 is a Canadian system that will replace RADARSAT-1, but it is a C-band radar optimized for observations of sea-ice. It cannot meet the objectives noted in this report. TerraSAR-X and Tandem-X are German radars operating at the even shorter X-band wavelength, and while they are very similar to existing U.S. high-resolution military technology, they likely will suffer from too much decorrelation for reliable InSAR over vegetated terrains. TerraSAR-X itself cannot supply data volume to meet our needs either. Tandem-X, operated in concert with TerraSAR-X, will probably obtain the highest quality digital elevation model of the Earth that will then exist. But it still cannot do repeat pass interferometry, the cornerstone of all of our planned major science objectives.

In summary, the panel notes that the reason for the U.S. science communities repeatedly proposing L-band InSAR missions is that it appears to be the only known technology for meeting our needs. Repeat pass InSAR methods will make the fine-scale and dense measurements needed to characterize the Earth for the several disciplines that have proposed it as the first priority for a new mission.

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9

Climate Variability and Change

OVERVIEW

If current climate projections are correct, climate change and variability over the next ten to twenty years will have highly noticeable impacts on society. Climate projections anticipate important changes in the intensity, distribution and frequency of severe weather, decreased sea ice leading to open ocean passageways in the Arctic, continued reduction of mountain glaciers, and continued trends toward record warmth (IPCC, 2001). The related impacts on agriculture, water resources, human health, and ecosystems are likely to drive a public demand for climate knowledge that will require significant changes in climate research. The magnitude and rate of the projected change, combined with the growth in infrastructure, are expected to increase climate-related risks. Research will focus on the predictive capability from seasons to decades and century time scales that are necessary to protect life and property, promote economic vitality, enable environmental stewardship, and help assess a broad range of policy options for decision-makers. Any vision for the future of Earth observations from space must anticipate the importance of an evolving climate. As the economic impact from climate change grows there will be both a change in research emphasis and a demand for renewed investment in climate research (Stern, 2007). Thus, observation systems of the future must recognize the following:

1. Sustained multi-decadal, global measurements and data management of quantities that are key to understanding the state of the climate and the changes taking place are crucial.
2. Climate change research, including the observational system, will be increasingly tied directly to understanding the processes and interactions needed to improve our predictive capabilities and resolve the probabilities associated with different outcomes.
3. Evaluation and assessment of model capability will increasingly be the focus of future measurement activities. Demonstrating model capability is likely to be a driver for developing and evolving observation systems and field campaigns.
4. The link between climate research and societal benefit will require a much greater emphasis on higher spatial resolutions in climate predictions, observations, and assessments.
5. The “family” of climate observing and forecasting products will continue to grow, involving innovative research into societal connections with energy, agriculture, water, human health, world economies, and a host of other areas, creating new public and private partnerships.
6. The demand to understand the connection between climate and specific impacts on natural and human systems will require a more comprehensive approach to environmental observation and modeling in order to integrate the multiple stresses that influence human and natural systems (i.e., climate, land use, and other human stressors such as pollutants).

These six points are based on the remarkably consistent set of evaluations of climate change and global change research made over the last two decades. The call for stable, accurate, long-term measurements of climate variables is a near universal requirement regardless of whether the reviews were focused on the adequacy of climate observations (NRC, 1999a), strategies for Earth science from space (NRC, 1985), integration of research and operations (NRC, 2000a; NRC, 2003a), improving the effectiveness of climate modeling (NRC, 2001a), enabling societal use of information (NRC, 1999b;

NRC, 2000b; NRC, 2000c; U.S. National Assessment, 2000), or providing an overview of the future direction of global change research (NRC, 1998a; NRC, 1999c; NRC, 2001b). Equally evident in these assessments are the conclusions that (1) we currently lack a suitable sustained climate observing system and (2) this gap limits progress in all aspects of climate research and applications. The most frequently cited reasons for our failure to develop a climate observing system are the pressure to produce short-term products that are suitable for addressing severe weather, the difficulty of maintaining a commitment to monitoring slowly changing variables, the lack of clear federal stewards with a defined climate mandate, and the disconnect between operational and research needs. Unfortunately, the difficulty of maintaining critical climate observations has been recently demonstrated by the loss of key climate monitoring elements on NPOESS.

The importance of tying observational systems more directly to the improvement of our predictive capabilities, and to understanding uncertainties, is equally well articulated in research strategies focusing on key climate feedbacks and improved estimates of climate sensitivity (NRC, 2001b; 2003b;c) and the key components of seasonal to interannual variability (NRC, 1994; 1998a). These strategies advocate a vigorous comparison of climate models and observations and a focus on specific observations that test how well climate simulations incorporate feedback processes and elucidate aspects of spatial and temporal variability. In addition, greater effort is needed to resolve the interactions at the atmosphere's boundaries (oceans, ice, and land surface/vegetation), enable an improved understanding of clouds and cloud feedbacks, and characterize the role of aerosols.

The growing emphasis on regional and higher spatial resolution predictions, expansion of the family of forecasting products, and the role of multiple stresses in environmental impact research is directly linked to the goal of realizing the full potential of climate research to benefit society. The value of climate information to society depends on knowledge of the nature and strength of the linkages between climate and human endeavors, improved understanding of the uncertainties associated with forecasts or predictions, the accessibility of credible information, knowledge of societal needs, and the ability of users to respond to useful information (NRC, 1999b; 2001c;d). Such research is now in its infancy, but the demand for research in this area will grow substantially.

The potential societal benefits are substantial. Even modest improvement in seasonal to interannual predictions have the potential for significant societal benefit in agriculture, energy, and management of weather-related risk (NRC, 1994; NRC, 1998a). The ability to characterize and/or reduce uncertainties in climate change prediction is a critical element in supporting energy and conservation policy related to global warming (NRC, 2001b). Our ability to assess potential climate impacts, and then to define adaptation and mitigation strategies, depends both on improving the effectiveness of climate modeling (NRC, 1998b; 2001a), and on implementing more comprehensive approaches to environmental study (NRC, 2000c). The first recommendation of the U.S. National Assessment of Climate Change Impacts (2000) calls for a more integrated approach to examining the impacts and vulnerabilities associated with multiple stresses. Several impacts and vulnerabilities are particularly noteworthy. Changes in the volume of water stored on land as ice and snow are of critical importance to coastal populations and infrastructure because of its impacts on sea level. Water resource management is strongly tied to climate and weather, and adaptation strategies are costly and often require decades to implement. Climate change research has considerable potential to help better anticipate adverse health outcomes, specifically related to heat mortality, changes in pattern and character of vector-borne diseases, and air quality. Finally, climate change research is a major factor in improving our ability to be better stewards of natural ecosystems.

This vision recognizes that the demand for knowledge of climate change and variability will intensify. Our objective is to improve our ability to anticipate the future and therefore increase our capability to utilize this knowledge to limit adverse outcomes and maximize benefits to society. Failure to provide this information carries high risks.

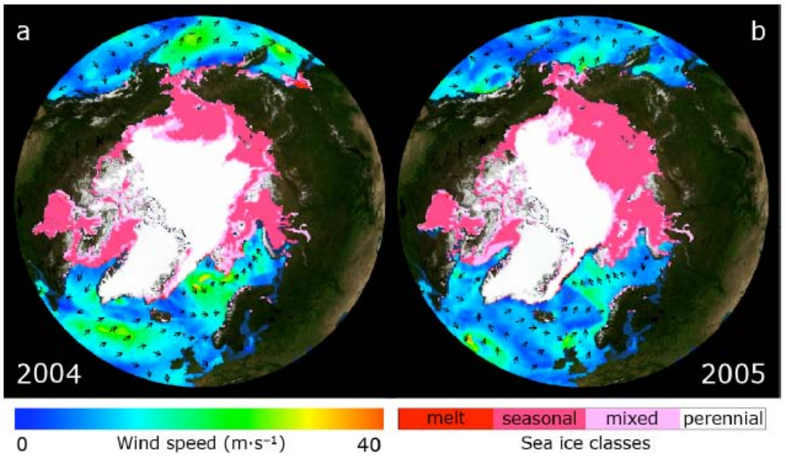

FIGURE 9.1. Reduction of Perennial Ice in Arctic Ocean. Arctic sea ice and wind vectors measured by QuikSCAT on 21 December 2004 (a) and 21 December 2005 (b). The sea ice classes include perennial or multi-year ice (white), mixed ice (pink), and seasonal or first-year ice (magenta). Over ice-free oceans, QuikSCAT wind speed is plotted from 0 m s^{-1} (blue) to 40 m s^{-1} (orange) and wind direction is represented by arrows. Land is denoted with the NASA 1 km land dataset. The decrease in the extent of perennial sea ice between 2004 and 2005 was 720,000 km^2, about the size of Texas. The anomalous perennial ice reduction was caused by a northerly wind anomaly (compared to 50 years of climatic data from NCEP) that transported sea ice out of the Arctic Ocean to the Greenland Sea in the south where it melted. [Nghiem et al., GRL, L17051, 2006].

BACKGROUND ON OBSERVATIONAL NEEDS AND REQUIREMENTS

The panel focused on four fundamental questions in its approach to envisioning specific space-based and supporting *in situ* and surface-based observations required for studies of the Earth's climate: (1) what governs the Earth's climate, (2) what forces climate change, (3) what feedbacks affect climate variability and change, and (4) how is the climate changing? In the coming decade, we will be challenged to better predict how the Earth will respond to the changes in atmospheric composition and other forcings. Our observations must document the forces on the climate system (including solar and volcanic activity, greenhouse gases and aerosols, changes in land surface and albedo), the characteristics of internal variability which can obscure forced changes and which may evolve in response to climate change, the feedback processes involving the atmosphere, land and ocean, biogeochemical cycles and the hydrologic cycle, and climate change itself.

Stripped to fundamentals, the climate is first affected by the long-term balance between the sunlight absorbed and infrared radiation emitted by the Earth. Thus, key elements to observe are the incident sunlight, the absorbed sunlight and the emitted infrared radiation. Achieving an understanding of how the system works requires the determination of the affecting influences, the absorbed sunlight and the emitted radiation. These include the composition of the atmosphere (such as greenhouse gases and aerosols), the state of the surface (whether snow or ice covered, whether vegetated or desert), and the effects of the various atmospheric components and the surface state on radiation loss to space. In addition, physical and chemical processes within the system feed back to affect the composition of the atmosphere and the surface state, such as the processes affecting water vapor and clouds. Other processes and conditions such as the extent of permafrost, subsurface concentrations of phytoplankton, and the ocean's thermohaline circulation are hidden from direct space view. Inferences must be drawn not only from records of space-based observations, but also from *in situ* as well as remotely sensed observations from surface-based, balloon, and suborbital platforms.

In its consideration of the specific observations to be made and the challenges and opportunities presented by the changes anticipated for the coming decade, the Climate Change and Variability Panel adopted the list of climate parameters in the 2003 Global Climate Observing System (GCOS) report

(GCOS, 2003). The panel then assessed the current observing capabilities and those planned for the coming decade, mostly from NPOESS. Table 9.1 (at the end of the chapter) lists the status of space observations, and in some cases supporting surface-based observations, of critical climate variables. Although this table provides a valuable perspective, its limitations should also be recognized: (1) in some cases, the table lists variables that can be obtained through several techniques but not all techniques are listed; (2) the table is limited to satellite observations which are in low-Earth orbit, although a number of the objectives listed in the table can also be achieved through retrievals using multi-spectral imagery and sounder data from platforms in geostationary and other orbits; and (3) few space-borne observations can be taken as a physical measurement in their own right, and interpretations are often revised as more comparisons are made between inferences based on space-borne observations and alternate measures of the physical variables. This evolution of knowledge will require the oversight of scientists and continuous evaluation by the climate research community as space-borne observations are transformed into the high-quality, long-term records that will be invaluable to climate studies and improved societal benefit.

The stratosphere plays a unique role in climate forcing, as well as responding in unique ways to global warming, greenhouse gases, solar UV, and volcanic aerosols. In many cases, observed changes are challenging to explain (e.g., Santer et al., 2003; Eyring et al., 2005). As with other variables critical to climate change, consideration of changes in the stratosphere require long-term climate data records of key stratospheric variables.

FIGURE 9.2 Marine stratocumulus over the Arabian sea imbedded in a plume of haze from the Asian subcontinent. The picture was taken from the NCAR C-130 during an Indian Ocean Experiment (INDOEX) research flight. Haze affects the number and sizes of cloud droplets and ice crystals thereby altering the amount of sunlight clouds reflect. The effect of haze on clouds is referred to as the aerosol indirect radiative forcing of climate and ranks among the largest uncertainties hampering assessments of climate change due to humans. (photo courtesy of Antony Clarke, U. Hawaii.)

Current Status and Needed Improvements

The description of current observations and needed improvements which follows is based on three basic requirements: (1) multi-decadal records of primary climate variables, (2) observations dedicated to inferring key processes affecting climate variability and change, and (3) opportunities for scientific exploration, innovation, and discovery.

Multi-Decadal Records

Increased scientific understanding and improved analysis depend substantially on the length and quality of the observational record—a key need is for space-based and surface-based observations spanning many decades.

Current Status of Multi-Decadal Records

The current scientific strategy for generating and sustaining long-term records, using space-based and ground-based instrumentation of finite lifetimes, is to achieve overlap of successive generations of observing systems. In this way, global records of a few decades duration have been constructed from space-based observations of variables such as sea surface temperatures, sea ice, atmospheric layer temperatures, the Earth's energy budget, and cloud properties. In the current strategy, overlapping observations are crucial in identifying and reducing the calibration uncertainties in current instruments that would otherwise exceed the sought-for geophysical changes.

The plans summarized in Table 9.1 show a heavy reliance on NPOESS for observations of key climate variables during the coming decades. The June 2006 de-scoping of the NPOESS program fails to satisfy the basic needs of climate science for the following reasons:

Firstly, instruments essential for climate science have been deleted from the NPOESS program. The following cancellations are of great significance to the climate sciences:

- CMIS (Conical-scanning microwave imager sensor). As currently proposed, the first NPOESS platform (C-1) will not embark a microwave imager/sounder. A solicitation for a "replacement" microwave imager/sounder is proposed for C-2 and beyond.
- APS (Aerosol Polarimetry Sensor). Aerosol observations for the medium-term will rely on the Glory research mission, with a launch anticipated for approximately 2008.
- TSIS (Total Solar Irradiance Sensor) has been cancelled.
- OMPS-Limb (Ozone Mapping and Profiler Suite) has been cancelled. With the deletion of the OMPS limb sounder, no monitoring of ozone profile below the ozone peak (where most ozone depletion occurs) is planned during the NPOESS/MetOp period. OMPS-Nadir is still included in the PM orbit.
- ERBS (Earth Radiation Budget Sensor) has been cancelled. The CERES instrument will fly on C-1, with no plan provided after C-1.
- ALT (Radar Altimeter) has been cancelled. No clear replacement plan is available as yet, other than a proposed reliance on a future Navy mission for altimetry.

There remains the option of deploying further DMSPs (i.e., one already built and in storage) in the mid-AM instead of the PM orbit. CrIS/ATMS and OMPS-Nadir will be flown only on the PM orbits, although VIIRS will be flown on all NPOESS platforms.

The NPOESS bus will have the capability (i.e., power and physical space) for the sensors listed above, and the Integrated Program Office (IPO) will plan for and fund integration of the sensors on the spacecraft within the NPOESS program, but only if the instruments are provided from outside NPOESS (i.e., by some other agency or partner).

The impact of these proposed changes is significant. As originally proposed, NPOESS already lacked the capabilities of the EOS era satellite systems, with VIIRS missing important water vapor and temperature sounding channels, with uncertainty about the capability of CMIS to provide useful passive winds, with OMPS having much lower horizontal resolution than Aura's Ozone Monitoring Instrument (OMI) and also lacking limb sounding, and with ALT in an orbit that makes removal of tides a challenge. Compared to the EOS provision of climate data in the current decade, the original NPOESS plan provided a weak set of observations for understanding climate change in 2010 and beyond. The 2006 de-scoped NPOESS plan will provide a still weaker set of climate observations with significant gaps in key variables.

Secondly, the 2006 proposed dates for NPOESS launches represent significant delays of several years in data provision:

- The NPOESS Preparatory Project (NPP) proposed launch date is delayed from 2006-2009.
- The proposed launch dates for NPOESS are 2013 for C-1 (in PM orbit), 2016 for C-2 (in AM orbit), 2020 for C-3 (in PM orbit), and 2022 for C-4 (in AM orbit).
- There will be no NPOESS platforms in mid-AM orbit; instead, the mid-AM orbit will be covered by MetOp.

The delays of the NPP and NPOESS will be felt immediately if overlap with the EOS Aqua and Aura platforms is lost. For example, the cancellation of CMIS and the delay of any microwave imager until 2016 would create a data gap in our record of sea ice concentration and extent, which extends from 1978 to present. Sea ice is one of the best documented and most rapidly changing elements in our climate system. In the Arctic, the lowest sea ice extent on record occurred in 2005, and September sea ice extent has been declining at a rate of about 8.5 percent per decade. This critical climate record requires continuation. In addition to sea ice mapping, passive microwave sensors are used to map the onset and extent of melt on the Greenland ice sheet, a key to assessing climate change and the contributions of ice sheet melt to rising sea level. In view of the fundamental role played by accurate long term Earth radiation budget measurements, and in view of the growing gap anticipated between the CERES observations on Aqua and the ERBS observations now scheduled for C-1 (proposed date of 2013), we face a major gap in some of the most fundamental measurements of the climate system.

Finally, we note that, regardless of the de-scoping, the NPOESS program lacks essential features of a well-designed climate observing system because:

1. NPOESS lacks a transparent program for monitoring sensor calibration and performance and for verifying the products of analysis algorithms. Moreover, the program lacks the direct involvement of scientists who have heretofore played a fundamental role in developing climate-quality records from space-borne observations. While NOAA has initiated plans for Scientific Data Stewardship (NRC 2004), these plans are in their infancy and NOAA's commitment to ensuring quality climate records remains untested and inadequately funded (NRC, 2005a).
2. NPOESS does not ensure the overlap that is required to preserve climate data records (CDRs). Instead, the NPOESS system is designed for launch on failure of a few key sensors. Failure of NPOESS instruments required for CDRs will very likely result in gaps of many months, making it difficult to connect long-term climate records and future measurements.
3. The NPOESS commitment to good radiometric calibration is unclear, particularly for the VIIRS visible and near infrared channels used to determine surface albedo, ocean color, cloud properties, and aerosol properties. It seems entirely possible that VIIRS will be flown as the NOAA AVHRRs were flown, with only preflight calibrations, leaving the in-orbit calibrations of these channels to drift. Furthermore, in its current configuration, VIIRS lacks the channels currently on MODIS in the 6.3 µm band of water vapor used to detect clouds in polar regions and in the 4.3 and 15 µm bands of CO_2 used to obtain cloud heights, particularly heights of relatively thin cirrus.
4. NPOESS only partly addresses the needed measurements of the stratosphere and upper troposphere. The primary variables for the stratosphere, viz. temperature, ozone abundance and some aerosol properties, will not be provided by NPOESS because of the loss OMPS-limb, APS and CrIS/ATMS. Other elements are poorly addressed by NPOESS plans, notably measurements of upper troposphere and stratosphere water vapor, aerosols, and the abundance of ozone-depleting compounds.

This decadal survey was designed to create a vision for the future of Earth observations from space. Reliance on the operational NPOESS system as a foundation for climate observations in a decadal vision for the climate sciences has failed as a strategy.

Needed Improvements and Products for Multi-Decadal Records

The collection and maintenance of the long-term records so crucial to understanding the climate system presents a number of challenges. Clear deficiencies in instrumentation and data analysis are evident in current plans, specifically in the transition to NPOESS. The needed improvements fall into two categories: (1) Actions required to address the loss of NPOESS measurements viewed as critical to climate research, and (2) Actions required to improve current and future observation strategies based on the lessons learned from space-borne climate data acquisition and utilization in past decades (e.g., MSU, ISCCP, the Global Aerosol Climatology Project).

1. NASA and NOAA should develop an immediate plan to address the loss of continuity of critical climate measurements. The most significant losses for climate include the microwave imager, Earth radiation budget measurements, total solar irradiance, and the loss of stratospheric measurement capability. Considerable care is required to ensure successful stop-gaps and long-term plans. Several options should be considered:

- Every effort should be made to provide instruments from outside of NPOESS (should Congress fail to act to restore NPOESS instrument losses) in order take advantage of the plan to fund integration of these instruments into the NPOESS platforms. Every option should be considered (e.g., substitute copies of existing instruments for the appropriate lost NPOESS measurements, for instance use of a copy of MODIS, AMSR-E or SSM/I).
- Every effort should be made to extend the life of Terra, Aqua, Aura, SORCE, and Glory to ensure the longest possible data records and to minimize or eliminate critical data gaps.

2. Significantly greater effort needs to be applied to improve current and future observation strategies based on the lessons learned from past missions:

- Improved instrument calibration is required for long-term climate records. Because of the uncertain future of instrument calibration within NPOESS and the likelihood of significant data gaps, the development of a space-borne calibration observatory to address accurate radiometry and reference frequencies is essential.
- For many variables, such as aerosol and cloud properties and water vapor concentrations, it is crucial to avoid orbital drift, which causes significant shift of several hours in the local time of the observations. Currently, the NPOESS satellites are designed to maintain their sun synchronous orbits and this requirement should not be relaxed.
- Mission failures and delays can introduce gaps which compromise the detection and understanding of spatial-temporal variability in the climate system. Consequently, until such an understanding of the climate system is achieved, and until techniques for ensuring radiometric and timing accuracies have been shown to succeed, sequential observations of key climate variables should be overlapped for sufficiently long periods to ensure useful comparisons.
- Reprocessing of critical data sets is required. The ability to reprocess data allows for 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 the earlier processing algorithms.

- Validation of geophysical products inferred from satellite remote sensing is essential. In developing CDRs, validation should be an almost continuous component, providing an independent check on the performance of the space-based sensors and processing algorithms.

The Climate Change and Variability Panel believes that the current strategy for continuity, of ensuring overlap between measurements, should be continued as recommended by GCOS (2003), CCSP (2003) and others (Ohring et al., 2005). For example, the different total solar irradiance instruments are tied to radiometric standards but produce measurements that depart from each other by amounts exceeding the claimed uncertainties. The panel recommends that substantial overlap be continued until a reliance on absolute measurement standards has been successfully demonstrated. However, the long-term success of climate measurements cannot always depend on redundancy and therefore requires new approaches, with future instruments designed and built to maintain in-flight calibration to absolute radiometric standards. Since temperature and humidity profiles derived from GPS occultations are likely to gain favor in long-term studies, measurements of time delay need to be tied to high-accuracy frequency standards as are now possible with the ultra stable oscillator flown on GRACE.[1] Ultimately, reliance on radiance and time measurements that are tied to absolute references will allow the climate record to tolerate gaps for some measurements, however the space-time variability of the climate during the gap in observations must be understood. Until such understanding is achieved, and the reliance on calibrated radiances and accurate time-delays is demonstrated through comparisons of measurements by different instruments on different platforms, the need for overlap remains.

Many of the calls for improvement in the satellite climate record, such as the need for radiometric calibration, launching to preserve the continuity as opposed to waiting for instrument failure, and the need to validate space-based inferred products, are themes that run through many previous reports (CCSP 2003; NRC 2004; Ohring et al., 2005). Less common are calls that address the culture and infrastructure required to provide the kind of societal benefits that are possible from these satellite observations (see sections 9.2.1.3 and 9.2.2 of this chapter).

Focused Process Studies

Process studies focus on understanding the climate feedback process and are critical to improving climate models. They are generally intensive, short-duration, repeated campaigns with ground-based, airborne, satellite, and modeling components. These studies typically require frequent, diurnally resolved measurements and a wide variety of simultaneous products, a need typically at odds with the accuracy and stability essential for achieving reliable long-term records.

Current Status of Process Studies

Many climate system processes and many causes of climate variability and change are not fully understood or adequately validated with observations. The large range in climate model estimates of the change in the global surface temperature in response to a doubling of CO_2 illustrates how choices in treating these processes—which vary greatly from model to model—can have sizable consequences. Reliable climate simulations require improved treatment of the processes known to be inadequate (NRC, 2003b; NRC, 2005b): (1) clouds, aerosols, and convective systems; (2) biosphere-atmosphere interactions; (3) sea ice, ocean circulation and ice-melt coupling; (4) ice sheet dynamics; (5) the fluxes of

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[1] Trenberth, K., B. Moore, T. Karl and C. Nobre, 2006: Monitoring and Prediction of the Earth's climate: A Future Perspective. *J. Climate*, 19, 5001-5008. Also see; Bengtsson, L, and Coauthors, 2003: The use of GPS measurements for water vapor determination. Bull. Amer. Meteor. Soc., 84, 1249-1258.

heat, momentum, water, and trace species across the interfaces of ocean-atmosphere, land-atmosphere, ice-atmosphere, boundary layer and free troposphere, troposphere-stratosphere, and ice-ocean; and (6) internal variability such as the ENSO.

Needed Improvements and Products for Process Studies

There must be a more deliberate effort to focus resources on the most critical weaknesses in predictive models, most specifically the six topics listed above. Networks of surface sites should be distributed to sample the widest possible process over the globe and designed to provide long-term observations of (1) clouds and aerosols and their impact on surface radiative fluxes, (2) fluxes of sensible heat, evaporation, and evapotranspiration, and (3) concentrations of key trace species and their surface atmosphere exchange rates. Such observations have proven invaluable in the validation of space-based inferences of aerosol and cloud properties and trace gas concentrations.[2] Properly incorporated in the scheme of climate data stewardship, the surface-based observations will produce local climatologies that not only enhance the utility of the record derived from satellites but also provide valuable information for society on local trends. In turn, satellite observations provide the global perspective and also facilitate the incorporation of the *in situ* and surface-based observations to develop regional scale trends.

Innovation and Discovery

Specific, focused investigations may emerge as urgent priorities because of new knowledge or unexpected events such as abrupt climate change. For example, a major volcanic or ENSO event, an unusual hurricane season, chronic atmospheric pollution plumes, or new insight into a poorly understood process such as convection may catalyze research interest or public attention and lead to substantial societal benefit.

Current Status of Opportunities for Innovation and Discovery

The panel notes that the NASA Earth System Science Pathfinder missions have provided important opportunities for space-based technical innovation and innovative scientific exploration. Three ESSP missions have flown and two are anticipated to launch in 2008. The timing of future opportunities is highly uncertain. Current budget restrictions have nearly eliminated this source of flexibility in the science that provides opportunities for the community to make critical measurements and to test new technologies. This loss of flexibility and innovation is highly significant. In addition, budget restrictions have led to the cancellation of DSCOVR, a completed satellite that would have provided innovative Earth and space observations from the L1 orbit but now sits in storage.

Needed Improvements and Products for Innovation and Discovery

Climate science needs to have the capability and flexibility to respond promptly and creatively to emerging climate change issues with the best technology. At the same time, the panel recognizes that these focused investigations can only be successful within the context of a broad understanding of the climate system, which in turn is made possible by the long-term climate data records described above.

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[2] A good example of the kind of coordinated efforts that can be developed is CEOP (Coordinated Enhanced Observing Period) under the WCRP GEWEX program <http://www.gewex.org/ceop.htm>.

The panel notes that alternative views of the Earth through new orbital vantage points, new instrumental and retrieval techniques, and new scientific hypotheses may all advance climate science in unpredictable ways. Some of the greatest challenges in improving the long-term record and in advancing our ability to predict change in order to benefit society (e.g., issues of calibration, cloud-climate feedbacks, convective processes, better understanding of surface fluxes) will require greater opportunities for innovation. New knowledge may also result from investigations that were not directed at climate variability and change. The necessary drive to design observing systems that address known deficiencies in knowledge should not preclude the tremendous contribution of curiosity-driven discoveries that have revolutionized the Earth sciences.

Implications of the Requirements in Developing Climate Data from Satellite Observations

Involvement of the Climate Science Community

The success of NASA's Earth Science Enterprise in developing records of climate variables that have been validated over long periods is unprecedented. The success was achieved through the involvement of many scientists who represented a wide range of interests within the climate community. This level of involvement must be continued regardless of the source of observations (such as NPOESS).

Accuracy and Time-Space Scales

To secure long-duration climate records, the observations must first have relative accuracy (precision) sufficient to detect the changes being sought. Ultimately, the acquisition of long-term climate records will require traceability to absolute calibration standards. In principle, once knowledge of the climate system becomes sufficient, accurate calibration standards may allow relaxation of the requirement that observations by independent instruments be substantially overlapped, at least for some climate variables. Clearly, the records must be able to properly characterize the seasonal and internal variations at appropriate spatial scales so that the relatively small secular changes can be reliably extracted.

Validation of Satellite-Derived Climate Data Products

Validation of the climate observations, for example, through comparisons with observations from balloons, aircraft and ground-based instruments, is crucial to ensure the quality of the data sets. For example, the panel notes that the DOE ARM sites and the federation of AERONET sites have been heavily relied upon to characterize cloud and aerosol properties as well as temperature and moisture profiles used in the validation of satellite-derived products. The operational weather network is also of significant importance. The existing networks need to be maintained. The networks also need to be expanded in terms of geographic extent and the types of measurements. While top of the atmosphere radiative forcing is often considered as being interchangeable with climate forcing, new insight calls for equal attention to the surface energy budget (NRC 2005b). The panel calls for the development of surface-based networks focused on climate observations and the development of the associated climate records as set forth in climate stewardship principles.

Use of Climate Records in Climate Model Development

Since simulations with climate models provide useful climate information, future observational systems need to recognize impending and ongoing model changes and improvements that will require validation and observational inputs. For example, global climate models are expanding to higher altitudes (top of the stratosphere and above), delineating more surface features (e.g., vegetation on land), utilizing higher spatial and vertical resolution, and adding more detailed process models in place of simple parameterizations. Quantitative datasets will be needed not only for model validation, but also for assimilation (e.g., cloud assimilation). Because climate records have and continue to play a fundamental role in climate model validation and development, the need for an Earth Radiation Budget Continuation Mission is reiterated. There is also a pressing need for measurements of the vertical distribution of water vapor, cloud ice and liquid water path, and convective processes.

Large Volume, Accessible Archives of Long-term Climate Observations

Climate science requirements have substantial implications for data management, distribution, access, reprocessing, scientific oversight, and value-added analyses that are all part of comprehensive data stewardship. These activities are crucial to provide the datasets that (1) prove useful for a wide range of climate science investigations, (2) are easy to access by scientists from diverse disciplines, and (3) facilitate the generation of accessible climate products for societal needs. The panel envisions a virtual observatory providing access to multiple data records, facilitating analysis of disparate observations and integration with model results. Ultimately, a new Climate Service (NRC, 2001d) may best meet the needs for climate science analysis, simulations, products, impacts and forecasts, as well as provide a coherent interface with public, political and other scientific disciplines. Climate science calls for a commitment to very long-term data stewardship.

HIGH PRIORITY SATELLITE MISSIONS

The Climate Change and Variability Panel approached the assessment of submitted RFIs (Request for Information) [3] and future observational needs from three different perspectives: (1) A "science traceability matrix" was constructed that connects science questions to elements of the climate system, candidate missions, and current and planned capabilities in order to identify gaps or inadequacies in the space-based observing system. (2) Responses to the RFIs were characterized as (a) elements of the climate record that must be maintained or extended, (b) observations required for understanding processes, or (c) exploratory research. (3) A disciplinary perspective was taken to determine specific priorities for different areas of research. The results from the three perspectives were generally consistent, giving some level of confidence in the panel's set of observational priorities. For each important climate measurement identified by the GCOS Second Adequacy Report, the science traceability matrix (Table 9.1) lists the measurement, strategy, current status, follow-on for 2010 to 2020, and related RFI responses and illustrates the set of planned and candidate missions.

The matrix is not intended to be exhaustive, but rather is a vehicle for assessing unmet needs in climate research. It is consistent with previous analyses of climate issues and research needs (e.g., IPCC, 2001; NRC 2000, 2003, 2004a, 2005). Further, the entries in the table should be viewed only as "recommended strategies" for making a particular set of observations in light of the unending need to refine interpretations of space-borne observations. Some of the approaches listed in the table, like those involving Earth's radiation budget components, have benefited from decades of advancement, while

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[3] The RFI submission process is discussed in chapter 2. The RFI is shown in appendix D and a summary of responses is shown in appendix E. A compact disc accompanying this report has full text versions of the RFI responses.

others, such as the characterization of cloud properties to come from the millimeter-wavelength cloud radar on CloudSat, are just beginning.[4] .

The matrix approach, combined with the perspective in the Overview (Part 1) and analysis of climate science requirements (Part 2), have guided the development of a proposed set of missions. These missions are not intended to address the problems in the current NPOESS program. The inadequacies of NPOESS, specifically the recently proposed cancellations, should be addressed separately as soon as possible, so that a progressive vision for the Earth sciences can be implemented.

The types of proposed missions include two categories essential to advance climate research and applications, both of which are needed to improve climate predictions for the benefit of society: (1) missions identified as major gaps and priorities, and (2) innovative concepts that extend beyond current instrumentation.

Identified Gaps and Priorities for Climate Change and Variability

Four missions are identified as major gaps and priorities for climate research and application (Table 9.1). Each includes specific proposals to address key science questions and specific instruments.

TABLE 9.1

Brief Description of Mission	**Variables**	**Type of Sensor(s)**	**Coverage**	**Spatial Resolution**	**Frequency**	**Synergies with other panels**	**Related Planned or Integrated Missions (if any)**
Cloud, Aerosols, Ice, and Carbon	Aerosol properties; Cloud properties; Ice sheet volume; Sea ice thickness; Ocean carbon; Land carbon	Scanning dual wavelength lidar, Multi-angle VIS/NIR polarized spectrometer, Hyperspectral imager, Radar	Global	30-50 m (hyper-spectral) 1 km (polari-meter)	~ days	Health Ecosystems Water Weather	ACE ICESat-II
Radiance Calibration	Radiation budget; Radiance calibration for long-term atmospheric and surface properties; Temperature, pressure, and water vapor; Estimates of climate sensitivity	Shortwave spectrometer, TIR spectrometer, Filtered broadband active cavity radiometer, GPS, Scanning radiometer, SIM	Global			Weather	CLARREO GPSRO NPP/ NPOESS (ERB sensor)
Ice Dynamics	Ice sheet surface velocities; Estimate of ice sheet sensitivity	InSAR	Global	~ meters		Solid Earth Water	ACE DESDynI NPOESS (CMIS)
Ocean Circulation, Heat Storage, and Climate Forcing	Surface ocean circulation; Bottom topography; Ocean-atmosphere interaction; Sea level	Swath radar altimeter, Scatterometer	Global (or near global)		Twice daily	Solid Earth Water Weather	SWOT GRACE-II XOVWM

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[4] Information about Cloudsat may be found at < http://cloudsat.atmos.colostate.edu/data>.

Climate Mission 1: Clouds, Aerosols, and Ice Mission (With Proposed Carbon Cycle Augmentation)

Mission Summary – Clouds, Aerosols, Ice, and Carbon	
Variables	Aerosol properties; Cloud properties; Ice sheet volume; Sea ice thickness; Ocean carbon; Land carbon
Sensor(s)	Scanning dual wavelength lidar; Multi-angle VIS/NIR polarized spectrometer; Hyperspectral imager; Radar
Orbit/Coverage	LEO, global
Panel Synergies	Health, Ecosystems, Water, Weather

Some of the most important uncertainties in global climate change involve: (a) the role of different types of aerosols in the Earth's radiation budget and hydrological cycle, (b) the importance of black carbon aerosols in suppressing clouds, altering precipitation and heating the atmosphere, (c) the rate of change in ice sheet volume, (d) the rate at which the oceans take up and sequester carbon, and (e) the change in land carbon storage and vegetation characteristics. These topics have been discussed by the IPCC, the NAS Earth Science and Applications from Space Report (2005), and the RFI responses submitted to the National Academy as part of the Decadal Survey. We propose a baseline mission, possibly to be flown in formation with the 1:30 NPOESS satellite, that will address items (a), (b), and (c), with a potential augmentation that would additionally address the carbon cycle, i.e., items (d) and (e).

Aerosol-cloud Forcing

Aerosol climate forcing is similar in magnitude to CO_2 forcing, but the uncertainty is five times larger (IPCC, 2001; Hansen and Sato, 2001). This assessment of uncertainty has not changed significantly from the earlier IPCC reports. Among the reasons for the uncertainty: aerosols have a short lifetime in the atmosphere (days to weeks) and not all aerosols are alike (Kaufman et al., 2002b). Furthermore, aerosols have an impact on cloud formation (the indirect effect) that amplifies their importance to the climate system (Twomey, 1977; Albrecht et al., 1989; Kaufman et al., 2005; Koren et al., 2005; Andreae et al., 2005). Black carbon (BC) aerosols, and other light absorbing particles, intercept incoming solar radiation, cooling the Earth's surface, heating the atmosphere above (Satheesh and Ramanathan 2000), and affecting cloud formation (Ackerman et al., 2000, Koren et al., 2004; Kaufman and Koren, 2006). Some calculations suggest the BC aerosol contribution to global warming may be as much as +0.5 W/m^2, a third of CO_2 forcing (Haywood and Boucher, 2000; Jacobson, 2001). Current estimates of BC concentration and effects on the climate system have a large uncertainty (Tegen et al., 2000).

A primary goal of Climate Mission 1 (CM1) is to reduce the uncertainty in aerosol forcing and aerosol feedbacks on cloud formation. As climate continues to change over the next 10 years and as urban pollutant emissions associated with aerosols continue to change, the Earth radiation budget and the hydrological system will respond. These changes and their effects on the climate system can be documented by a payload that includes a cloud/aerosol lidar, a multi-angle spectrometer/polarimeter and a cloud radar. This mission could fly in formation with the 1:30 NPOESS satellite (C-1) which, with the VIIRS instrument, would provide visible and NIR bands used in aerosol retrievals. Combined with the NPOESS instruments, the instrument package of CM1 mimics the relevant capabilities of the A-Train (Aqua MODIS, Aura OMI, CloudSat, CALIPSO, POLDER and Glory), while significantly advancing the technology to better accuracy, finer resolution and greater spatial coverage, all necessary to understand aerosol-cloud interaction. This package will also address ice sheets (see below) and with the addition of a hyperspectral imager, either on the same platform or co-flying on its own satellite, this mission can additionally address the ocean and land carbon goals mentioned above.

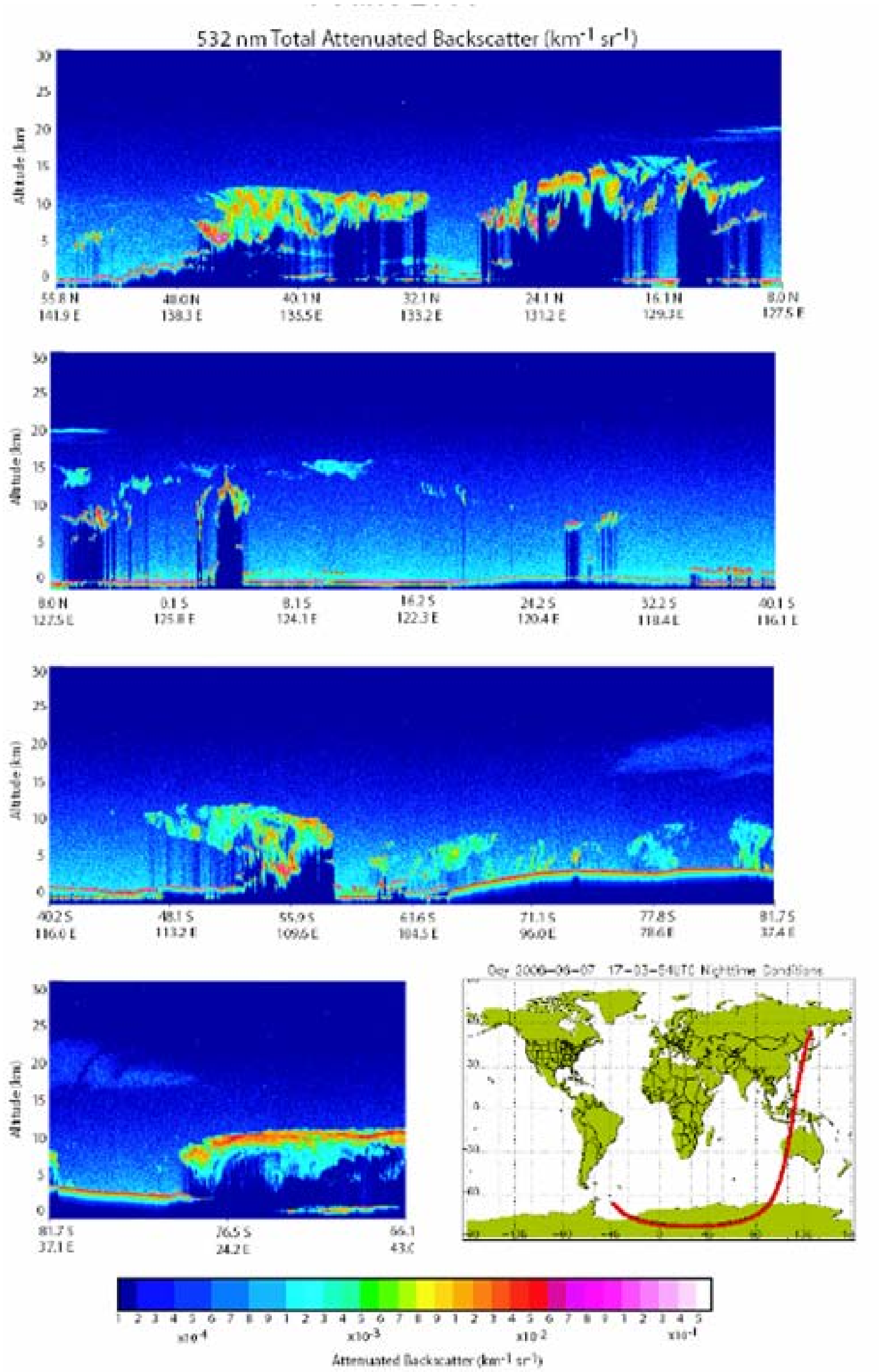

FIGURE 9.3 First observations obtained with the CALIPSO lidar launched April 28, 2006. The attenuated backscatter returns show, in addition to the deep convective clouds at middle to high latitudes and the tropics, a stratospheric aerosol plume at 20 km over the tropics from the eruption of Soufriere two weeks prior to the observations and polar stratospheric clouds, also at 20 km over Antarctica. The lidar observations in conjunction with other A-train data promise many new insights into clouds, aerosols, and cloud-aerosol interactions. (Courtesy of D.M. Winker and the CALIPSO Science Team, NASA Langley Research Center.)

The primary instrument on CM1 is a multi-angle spectrometer-polarimeter like APS but with a POLDER-type wide cross track swath (±50º) and finer spatial resolution for better retrievals of cloud microphysics. The spectrometer-polarimeter will have capability to observe the cloud polarized phase function or the "rainbow" (Breón and Goloub, 1998), and thus retrieve important cloud microphysical information necessary to understand the onset of precipitation in convective clouds. Such studies are not possible with the current, 100 km resolution. This instrument can determine the scattering properties of aerosols over a wide range of wavelengths and with the polarization information can provide information on black carbon. By observing aerosols over the ocean both on and off the glint angle, the absorption properties of the aerosol can be determined and the black carbon inferred (Kaufman et al., 2002a). Experience with the TOMS, EOS MISR and POLDER sensors (POLDER, Breon et al., 2002; MISR, Kahn et al., 2001: TOMS, Torres et al., 1998) shows that multi-angle measurements at several wavelengths, including the UV combined with polarization, provide an optimal strategy.

The second proposed instrument is a cloud/aerosol lidar. Near simultaneous lidar measurements of the aerosol height are critical for retrieving aerosol properties as well as for retrieving the effect of aerosols on clouds. This approach will soon be tested with CALIPSO now successfully launched into the A-train formation with the Aqua and CloudSat missions.[5] The CALIPSO lidar provides a single nadir measurement, but technology exists to provide a multi-beam system that can produce a much wider cross-track swath.

The third instrument on CM1 is the cloud radar. The cloud radar is needed to measure cloud formation, cloud hydrometeor properties and cloud morphology in response to aerosols. The primary cloud processes of interest to CM1 include the onset of cloud formation, cloud morphology, the role of aerosols in the development and evolution of cloud hydrometeor profiles, and the microphysical basis of the resultant cloud radiative properties. The observational goals for a Cloud Profiling Radar (CPR) therefore include estimating the cloud droplet concentration and size distribution, and the cloud hydrometeor type. The goal of these measurements is to estimate the liquid / ice water path, the optical path length and extinction coefficient, and the variability of these parameters as relates to the effects of aerosols.

The cloud radar must be sensitive to cloud droplets well below the precipitation size range. Further, cloud radar measurements should mesh smoothly with the lidar measurements of aerosol and nascent cloud properties. These goals dictate the choice of a short wavelength that will be optimized for the smallest hydrometeors, and the smallest reasonable sampling volume, or spot size.

Experience indicates the choice of 94 and 35 GHz radars, and even higher frequency radiometer systems for measurement of such cloud parameters. For spacecraft, we can use the CloudSat[6] and EarthCARE[7] CPR designs. The antennas for both CPR systems are offset paraboloids. The advantage of such systems is the extremely low side-lobes but they can only operate in the nadir. An alternative approach is to use patch antennas that can steer the beam to multiple positions across the track. Patch antennas increase the side-lobes and may limit peak power and system reliability. Scanning to approximately ±10º should be possible without much degradation of vertical resolution.

Ice Sheet and Sea Ice Volume

Mass balance of the Earth's great ice sheets and their contributions to sea level are key issues in the area of climate variability and change. The relationships between sea level and climate have been identified as critical areas of study in the IPCC Assessments, the Climate Change Science Program Strategy, and the U.S. IEOS. Because much of the past and future behavior of ice sheets is manifest in

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[5] The other members of the A-train are the AURA and PARASOL spacecraft.

[6] CloudSat CPR specifications from http://cloudsat.atmos.colostate.edu/instrument.

[7] http://esamultimedia.esa.int/docs/EEUCM/EarthCARE_handout.pdf.

their shape, accurate observations of ice elevation changes are essential to understanding their contributions to sea level rise. ICESat, using a dual wavelength lidar with high altimetric fidelity, has provided episodic but high quality topographic measurements allowing estimates of ice sheet volume. High accuracy altimetry is also proving valuable for making long-sought estimates of sea ice freeboard and hence sea ice thickness, which is a parameter essential for ice volume determinations, ice thickness change determinations, and estimations of the flux of low-salinity water out of the Arctic basin and into the marginal seas. As yet, altimetry is the best (and perhaps only) technique for making this measurement on basin scales and with seasonal repeats. This is particularly important for climate change studies because sea ice areas and extents have been well observed from space since the 1970s and have been shown to have significant trends, but sea ice thicknesses do not have such a record. As climate change continues, ongoing, frequent measurements of both land ice (monthly) and sea ice (daily) volume will be needed to observe trends, update assessments and test climate models. The cloud/aerosol/ice lidar proposed above can provide altimetric information with the precision of the ICESat instrument and allow fundamental questions of ice sheet and sea ice volume to be addressed. Combining altimetry with a gravity measurement at a higher precision than GRACE would optimally measure both changes in ice sheet volume and mass and directly contribute to determining the ice sheet contribution to sea level rise.

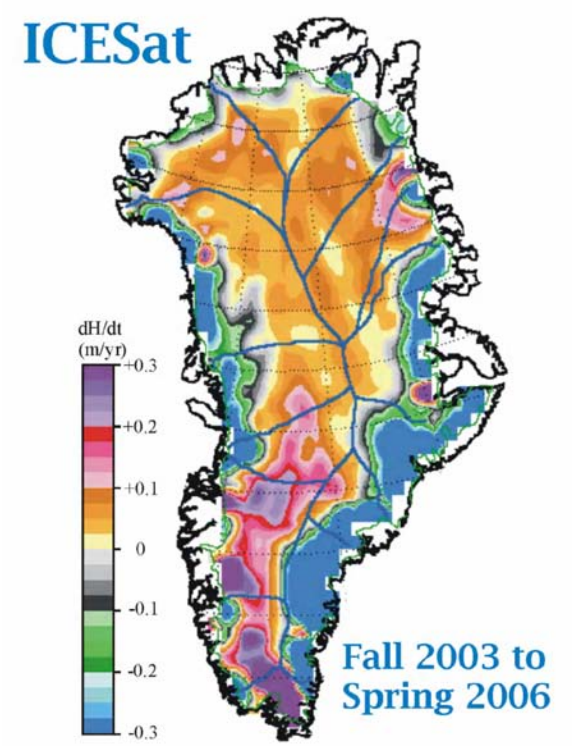


FIGURE 9.4 Elevation change (dH/dt) of the Greenland ice sheet between fall 2003 and late spring 2006 from ICESat data. ICESat's laser altimeter measures elevations over the entire ice sheet for the first time, including the steeper margins where mass losses are largest. The large areas of thinning (dark blue) on the upper left (west) and lower right (east and southeast) are where recent GRACE analysis (Luthcke et al., 2006) showed significantly increased mass loss compared to the period 1992-2002 (Zwally et al., 2005) and where outlet glaciers have accelerated (Rignot and Kanagaratnam, 2006) and ice-quakes have increased (Ekstrom et al., 2006). Significant inland growth, especially in the southwest, is at least in part due to increasing precipitation. The high-resolution laser mapping detects alternate areas of thickening and thinning around the ice sheet margin, as well as the changes inland, providing details of the competing processes affecting the mass balance as climate changes. Results are from repeat-track analysis (8 sets of 33 day tracks), which is enabled by ICESat's precision off-nadir pointing to reference tracks to ± 100 m. SOURCE: Courtesy of Jay Zwally, NASA ICEsat Project Scientist.

Orbit and Timing Issues

For aerosol and cloud measurements, the ideal configuration would be to fly CM1 at the same orbit altitude as the NPOESS spacecraft (~820 km). This would allow CM1 to take advantage of the VIIRS and NIR sensors as well as the Earth radiation budget measurements. CM1 would then provide the aerosol and cloud polarimetry measurements that should have been provided by APS on the original NPOESS payload. One technical difficulty with this payload is that an 820 km orbit is a significant challenge for the lidars as their signal drops off as $1/r^2$ (thus higher orbits require more power and reduce the lifetime of the lidar). A lower orbit would be feasible if the VIIRS visible and IR bands could be included in the polarimeter. Another problem is that the sun-synchronous polar orbit with a 98° inclination is not ideal for ice sheet measurements since polar coverage is reduced. The ICESat mission, for example, is in a non-sun synchronous polar orbit at 600 km with a 94° degree inclination which provides greater coverage of the polar regions.

Given the rapidity of the change in polar sea ice and ice sheets (e.g., Yu et al., 2004; Zwally et al., 2005; Parkinson, 2006) and the limited remaining lifetime of ICESat, a critical gap would arise if the new measurements were not made prior to the 2015 possible launch of CM1 and the C1 NPOESS mission. Hence, the panel advocates the earlier launch of an ICESat-lite mission, carrying the red but not the green ICESat laser and following the ICESat orbit, to continue the assessment of polar ice changes. Unofficial costing of such a mission suggests that it can easily fit within the ESSP budget category and could be developed for launch by 2010.

Proposed Augmentation—Carbon Sources and Sinks

The proposed payload can be augmented at little additional cost to meet important objectives for carbon sources and sinks. Although the forcing uncertainty due to long lived greenhouse gases is small, there are significant uncertainties in the sources and sinks of carbon that limit the predictability of future CO_2 abundances. The uncertainty in the CO_2 budget may be due either to additional ocean sinks or to increases in land biomass storage through the re-growth of forests.

Land carbon. Understanding land carbon storage is a critical factor in predicting the growth of atmospheric carbon dioxide and subsequent global climate change. The cloud/aerosol lidar can also be used to measure the canopy depth and thus estimate land carbon storage, as demonstrated from aircraft using the LVIS sensor (Dubayah et al., 1997). An approved, but since cancelled ESSP mission (the Vegetation Canopy Lidar (VCL)) ran into technological problems that have since been solved. Furthermore, new technology has recently been developed to allow lidars to produce multiple measurements across the swath, greatly increasing the coverage. The limited ICESat data over land are also being used for canopy height estimation. Combined with a lidar biomass volume assessment, the ideal land carbon mission would include a hyperspectral imager to assess vegetation type. Hyperspectral measurements of reflected solar radiation with a spectral resolution of 5 to 10 nm in the range 320 to 2500 nm including bands in the thermal infrared (10 to 12 μm) and a spectral resolution better than 0.5 nm in a few spectral windows from 350 nm to 765 nm, and in the O_2 A-band (760 nm) for cloud height would provide the basic capability of land vegetation type assessment. Horizontal resolution of 30 to 50 m with a 60 km swath or less would be ideal. This small swath width suggests that the instrument should point to special targets as the EO-1's Hyperion instrument does now. The additional thermal infrared bands can be used to track water temperature and estimate thermal cloud properties.

2 Ocean Carbon. The ocean is a rapid processor of carbon and a major uncertainty in the global carbon flux. The estimated ocean carbon uptake is about as large as the total uncertainty in the carbon budget (IPCC, 2001), and estimates from O_2/N_2 flux ratios suggest that the current estimates may be too large by a factor of two (Plattner et al., 2002). Carbon uptake by the ocean is also influenced by climate change through changes in wind stress and salinity that produce a concomitant response in zones of upwelling, mixed layer depth, aeolian fertilization, the marine ecosystems and the export of carbon. All of these changes together will alter the oceanic uptake of CO_2. Evidence of such control is seen in the changes in the growth of atmospheric CO_2 during the last El Niño, in which a ~5 percent change in Net Primary Production occurred. In the ocean, Net Primary Productivity is dominated by phytoplankton growth (Behrenfeld et al., 2001), and the ideal measurement combines a spectrometer to measure chlorophyll and dissolved organic matter (DOM) and a lidar to measure the aerosol optical depth to correct the passive visible and UV measurements of the spectrometer. This combination of instruments is very similar to the aerosol/cloud/ice payload, so both science objectives can be met if the relevant visible and UV bands can be added to the spectrometer and the hyperspectral imager. The hyperspectral imager meets the requirement of high horizontal resolution in coastal zones, and the spectrometer meets the requirements for a broad swath in pelagic zones.

Summary

The primary objective of Climate Mission 1 is to quantify aerosol/cloud interactions. The primary instruments are a multi-beam altimetric lidar, a spectrometer/polarimeter, and a cloud radar. A key second objective is to obtain ice sheet and sea ice topography measurements and from them to estimate sea ice thickness and ice volume change. With the addition of a fourth instrument, a hyperspectral imager, either included with this payload or as a co-fly, this mission can measure land carbon storage and ocean carbon fluxes. We envision CM1 possibly flying with the C-1 NPOESS satellite to take advantage of the VIIRS, CrIS/ATMS, and Earth radiation budget sensors on that mission. CM1 provides critical polarimetry and cloud measurements de-scoped from NPOESS.

CM1 (with C-1) would be in a sun-synchronous orbit at 98.7º inclination, with a launch in approximately 2015. With this orbit inclination, a significant area of the Antarctic ice sheet and the sea ice of the central Arctic Basin will not be seen by the CM1 altimetric lidar. Since rapid ice sheet changes are a significant climate issue, we recommend the earlier launch of an ICESat-lite mission in an orbit appropriate for polar ice coverage, to provide closer continuity with ICESat data. The panel believes that a ICESat-lite would fit into the small mission category.

CLIMATE MISSION 1: TABLES

Science and application capabilities

Key Science Question	Measurement	Instruments
How do aerosols change cloud formation, brightness and precipitation?	Aerosol properties, height, cloud properties and height, cloud droplet distribution	Multi-beam altimetric lidar (aerosol height) Spectro-polarimeter Cloud radar
How is ice sheet volume changing?	Altitude of ice sheets	Multi-beam altimetric lidar for ice sheet altimetry
How is sea ice thickness changing?	Ice freeboard	Multi-beam altimetric lidar for ice free-board
What are the reservoirs of carbon on land?	Vegetation biomass and type	Multi-beam altimetric lidar for vegetation biomass Hyperspectral imager
What are the reservoirs of carbon in the ocean	Ocean color and CDOM	Spectro-polarimeter Hyperspectral imager Multi-beam lidar (for aerosol correction)

Instruments and science objectives

Instrument	Aerosol Properties	Cloud Properties	Ice sheet volume	Sea Ice thickness	Ocean carbon	Land carbon
Scanning dual wavelength altimetric lidar	Primary	Primary	Primary	Primary	Secondary	Primary
Multi-angle Visible/NIR/Polarized Spectrometer	Primary	Primary	NA	NA	Primary	Secondary
Hyperspectral imager	Secondary	Secondary	NA	NA	Primary	Primary
Cloud Radar	NA	Primary	NA	NA	NA	NA

Instrument requirements

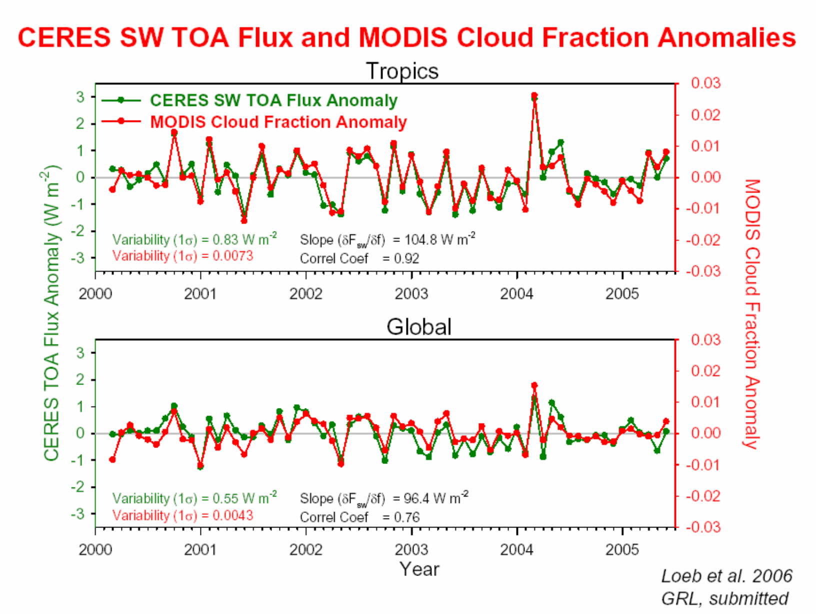
Instrument	Requirements	Comments
Scanning lidar	Scanning	Cross track multiple beams to increase coverage for aerosols and canopy
	Dual wavelength	512 nm for clouds and aerosols
	Precision altimetry of ~1 cm	Nadir beam
Multi-angle wide swath spectrometer-polarimeter (may be more than one instrument)	Nadir and off nadir measurements at selected wavelengths, wide swath coverage	Polarization accuracy equivalent to APS Usual aerosol wavelengths extending to the UV. Some special wavelengths for ocean color and DOM. Some wavelengths with 1 nm resolution for retrieval of ozone and NO_2 and HCHO for air quality.
Point-able hyper spectral imager	0.31-2.4 µm 10 nm resolution 60 km swath – 30-50 m resolution; a few bands in the 10-12 µm region	Retrieves plant functional types, ocean color. Small swath requires pointing. High spatial resolution retrievals of cloud and aerosol properties
Cloud radar	94 GHz radar with pointing	Pointing capability allows targeting of cloud systems for increased coverage

Climate Mission 2: Radiance Calibration and Time Reference Observatory and Continuation of Earth Radiation Budget Measurements

Mission Summary – Radiance Calibration	
Variables	Radiation budget; Radiance calibration for long-term atmospheric and surface properties; Temperature, pressure, and water vapor; Estimates of climate sensitivity
Sensor(s)	Shortwave spectrometer, TIR spectrometer, Filtered broadband active cavity radiometer, GPS, Scanning radiometer, SIM
Orbit/Coverage	LEO, global
Panel Synergies	Weather

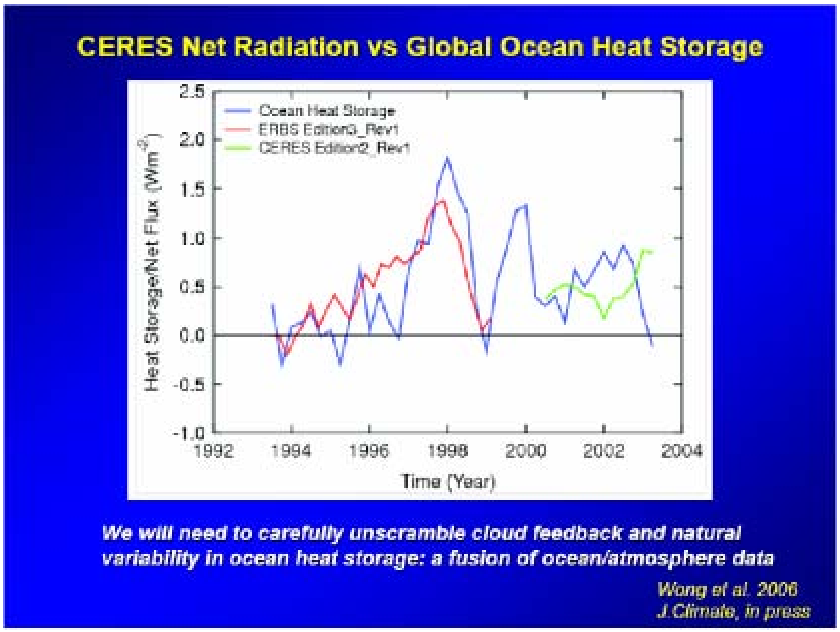
A strategy based on overlapping missions has been the primary tool to ensure continuity of measurements. However, the long-term success of climate measurements requires new approaches, with future instruments designed and built to maintain in-flight calibration traceable to absolute radiometric standards. Ultimately, reliance on radiance and time measurements that are tied to absolute references will allow the climate record to tolerate gaps for some measurements, once the space-time variability of the associated variables has been characterized and is largely understood. Temperature and humidity profiles derived from GPS occultations require the measurement of accurate time-delays from GPS or equivalent systems and thus a time reference measurement is required using ultra stable oscillators as flown on GRACE. The panel recommends the development of a Radiance Calibration and Time Reference Observatory (RCTRO) that will help ensure the long-term success of climate measurements by providing absolute radiometric references and accurate time-delays to compare with the various Earth viewing instruments on orbiting platforms.

Nonetheless, until sufficient understanding of the variability in the climate record is achieved, the requirement for measurement overlap remains. One area needing immediate attention is the threat of a considerable gap occurring in highly accurate measurements of Earth’s Radiation budget. For more than two decades, Earth radiation budget observations from ERBE and CERES have been used to assess climate model simulations of the radiation budget (Wielicki et al., 2003), cloud radiative forcing (Potter and Cess 2004), and sunlight reflected by aerosols over oceans (Loeb and Manalo-Smith 2005). The design of Earth radiation budget sensors coupled with sustained efforts over the years to (1) ensure the radiometric accuracy and (2) validate the inferred radiative fluxes (Loeb et al., 2003a, b, 2005) has led to a long term record of highly accurate measurements. Such measurements allow the use of Earth’s net radiative flux to follow trends in the total energy stored by the global oceans (Wong et al., 2006). Such trends are typically of order 0.5 Wm^{-2} per decade and thus demonstrate the feasibility of achieving accuracies comparable to those of the radiative forcing predicted for this century. As the record is extended, comparisons of the net radiative flux at the top of the atmosphere against independent measures of ocean heat storage will begin to constrain estimates of global-scale climate sensitivity. But, this accuracy has been achieved through overlapping observations of the broadband radiances from multiple sensors—the wide field of view sensors from ERBE and the CERES scanning radiometers on TRMM, Terra, and Aqua. Without the benefit of such overlap, the ability to achieve and to demonstrate the long term stability of the energy budget measurements would have been sorely compromised. For these reasons, the panel also recommends an Earth Radiation Budget Continuation Mission or the flight of CERES on NPP to bridge the growing gap between the CERES observations of Terra and Aqua and those of the NPOESS ERBS planned for C-1 (2013 launch).



Loeb et al. 2006
GRL, submitted

FIGURE 9.4 Five-year record of monthly mean anomalies in reflected sunlight (Wm^{-2}) derived from the CERES broadband radiometers and cloud cover derived from the MODIS 1-km imager. Cloud cover and reflected sunlight are highly correlated and variations in both, when averaged over the Earth and for monthly means, are remarkably small, ~0.5% for both quantities. The results illustrate the high stability achieved with the NASA Earth Observing System sensors. (Loeb et al. 2006 submitted to GRL.)


CERES Net Radiation vs Global Ocean Heat Storage

We will need to carefully unscramble cloud feedback and natural variability in ocean heat storage: a fusion of ocean/atmosphere data

Wong et al. 2006
J.Climate, in press

FIGURE 9.5. ERBE and CERES observations of the net radiation budget track observations of the net heat storage of the global oceans. Long term observations of the net radiation budget and heat storage of the ocean together will challenge the ability of climate model simulations to correctly predict major climate feedbacks such as the water vapor and cloud feedbacks and the climate response. (Wong T. et al., J. Climate, 19, 4028, 2006).

Radiance Calibration and Time Reference Observatory

Estimation of trends in the climate records of the TIROS-N series has been complicated by the lack of radiometric calibration for instruments on different platforms. Trend estimation direct from the measurements is further complicated by drifts in the orbits of the operational satellites, which cause shifts in the local times of the observations and in orbit altitudes; orbit drift is not a problem for modern assimilation systems. In the EOS era, effective orbit control has largely eliminated problems associated with orbit drift, but maintenance of the radiometric calibration of sensors on different platforms remains a challenge. Onboard calibration, particularly of reflected sunlight, was not undertaken for the TIROS-N series of satellites. It remains to be seen if it will be undertaken with NPOESS. Lack of calibration of the short-wave channels compromises long term measurements affected by aerosol and cloud properties as well as surface albedos. This panel believes a mission should be developed to provide in-space calibration standards against which to monitor the calibration histories of sensors measuring reflected sunlight, emitted infrared radiation, and GPS time delays. Such a mission would overcome the long-standing problem of cross platform instrument comparison. The mission will fulfill a principal objective of the vision (Part I) by meeting the continuing need to maintain the long term accuracy of many space-based observations (NRC, 2004; Ohring et al., 2005).

The concept for the Radiance Calibration and Time Reference Observatory (RCTRO) was developed from information in RFI responses (Climate Benchmark Constellation and Climate Calibration Observatory RFIs). RCTRO would carry a short-wave spectrometer (0.2-3 μm) and a thermal infrared spectrometer (3-100 μm) both with a nadir field of view ~ 100 km, plus two (0.2-100 μm) broadband active cavity radiometers having nadir fields of view ~ 500 km with one filtered (0.2-3.5 μm) for short-wave radiances. The relatively large fields of view are proposed to simplify the designs of the instruments and to enhance the radiometric signal to noise to achieve high radiometric accuracy. The radiometers would be built with the utmost radiometric accuracy feasible in such instruments and would be designed to maintain accurate radiometric calibration on orbit through onboard sources and solar and lunar calibrations. RCTRO would also carry a GPS receiver that has a high-precision, high-stability oscillator for accurate time delay measurements.

The strategy would be to incorporate at least three satellites into the RCTRO. Two satellites would be placed in precessing orbits separated by six hours in equatorial crossing time. The third satellite would provide a backup in the event of failure of one of the orbiting satellites, thereby ensuring overlap of observations as desired for climate data records (CCSP, 2003; Ohring et al., 2005). The satellites would have a nominal lifetime of six years and would under-fly all relevant space-borne sensors on both operational and advanced concept measurement mission satellites. The observations from the high spatial resolution imagers and sounders would be mapped to the fields of view of the standard shortwave and long-wave spectrometers. The spectrometers would have sufficient spectral resolution to reconstruct the filter functions of the instruments being calibrated. Broadband radiometers are included to (1) check the consistency of the integrated radiances from the spectrometers and (2) provide calibration checks for future Earth Radiation Budget Sensors that the panel recommends be carried on NPOESS. Both the spectrometers and the broadband radiometers would be designed to adjust sun-target-satellite geometry so as to map the performance of the various imagers and sounders across the angular domains of their scans.

Because much of the infrastructure for this active limb sounding technique already exists in the form of the Global Positioning System (GPS) satellites, GPS radio occultation offers an ideal method for benchmarking the climate system.[8] GPS radio occultation profiles from low Earth orbit provide the refractive properties of the atmosphere by observing the time delay of GPS signals induced by the atmosphere as the ray-path descends in a limb-sounding geometry. The index of refraction is directly related to pressure, temperature, and water vapor concentration in a way wherein the refractive index can

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[8] Goody, R., J. Anderson and G. North, 1998: Testing climate models: an approach. *Bull. Amer. Meteor. Soc.*, 79, 2541-2549. Also see, Trenberth, et. al., op. cit. fn. 1.

be easily simulated from model output. Moreover, GPS occultation offers an accurate measurement of geopotential heights on constant pressure surfaces throughout much of the troposphere and stratosphere and thus offers the opportunity to directly observe thermal expansion of the troposphere in response to forcing. GPS radio occultation is traceable to international standards because the raw observable, the timing delay induced by the atmosphere on the occulted GPS signal, can be tied directly to the international definition of the second by a near real-time chain of calibration.

Future GPS sounding measurements will be enhanced by the availability of the Galileo satellite navigation system, to be implemented by the European Union in the near future. The Galileo system will double the number of available transmitters for Global Navigation Satellite System (GNSS)-based atmosphere sounding. Also, the signals of the Russian GLONASS satellites have the potential to be used for the application of atmosphere sounding techniques. If GPS occultation data sets are to be used in climate change studies, measurements from various low Earth orbiting satellites (e.g., CHAMP, Oerstead, COSMIC) with their attendant onboard oscillator drifts, and the different GNSS implementations, will require a comprehensive calibration effort. RCTRO satellites carrying a GPS receiver with a high accuracy ultra stable oscillator (USO), such as that of the GRACE receiver, will facilitate relative calibration of the various occultation measurements. In view of the importance of the occultation measurement and the accurate positioning on the satellite for other sensor measurements, we recommend that GPS receivers be a standard part of both NASA and NPOESS low Earth orbit payloads. Accurate, long term radiometric calibration of space-borne sensors and time-referencing of GPS receivers will greatly facilitate detection of trends in a large number of climate variables.

Earth Radiation Budget (ERB) Continuity

The Earth radiation budget has been measured continuously from space for more than two decades. The CERES project has demonstrated the capability of obtaining highly accurate radiative fluxes when the broadband radiances obtained with the radiometer are interpreted through scene identification achieved through the analysis of collocated multispectral imagery data (Loeb et al., 2003a and 2005). The identification allows the selection of appropriate anisotropic factors that are used to convert the CERES broadband radiances to radiative fluxes. The panel calls for the refurbishing and launching well prior to 2013 the CERES Flight Model-5 (FM-5) scanning radiometer, which is now in storage and currently in line to become the NPOESS ERBS on C-1. The refurbishments are minor and entail activities that have been recommended for the NPOESS ERBS: (1) change the mirror attenuator mosaic to improve the on-orbit solar calibrations and (2) replace the CERES narrow 8 to 12 μm window filter, now constituting one of the three CERES channels, with the ERBE long-wave filter. The panel recommends that the CERES FM-5 be launched on NPP so that the scene identification can be performed with the collocated VIIRS imagery. The panel recommendation also calls for the development of the NPOESS ERB Sensors that were to be flown on the afternoon satellites (now, C-1 and C-3).

Like the Earth radiation budget, the total flux of sunlight reaching Earth, like the Earth radiation budget, has also been measured continuously from space for more than two decades. The measurements have established that total solar irradiance varies with solar activity. The solar spectral irradiances are known to be rather variable at UV wavelengths and much less variable at visible and near IR wavelengths. This wavelength dependence, however, is poorly known because of an almost complete lack of observations prior to the launch of the SORCE mission in January 2003. Since then, the Spectral Irradiance Monitor (SIM) on SORCE has measured the solar spectral irradiance from 0.2 to 2 micron. NPOESS was proposed with TSIS (Total Solar Irradiance Sensor, a combination of a Total Irradiance Monitor (TIM) and SIM), but TSIS is now to be eliminated. The lack of a continuation in SIM measurements threatens to end the spectral irradiance record before a complete solar cycle has been observed. The panel thus also recommends that SIM be added to NPP or Glory to ensure the continuation of the spectral measurements to cover at least a full solar cycle.

The existing SIM instrument meets the needs for solar irradiance in its current configuration, but a number of enhancements would improve its performance and the overall value of the measurement: (1) Extended wavelength coverage further into the near infrared would provide calibration data for other near-infrared sensors, spectral information over a larger fraction of the total solar irradiance, and solar variability data at these longer wavelengths. (2) Improved absolute detector technology with improved dynamic range and response time would ease planning and scheduling and make the instrument a better match for future, yet to be defined spacecraft.

Summary

The RCTRO is designed to (1) provide radiometric calibration standards for all space-borne sensors that measure radiances ranging from the UV through the far infrared thereby achieving accurate narrowband radiances which are the starting point for developing long term records of atmospheric and surface properties needed to advance the science of climate and climate change and (2) provide a time reference standard to accurately determine the relative time delay measurements of the various GPS navigation satellite systems that will be launched in the coming decade. The RCTRO is a system of three satellites with two in precessing orbits separated by six hours and a third ready to launch in the event of a failure of one of the orbiting satellites. The satellites carry spectrometers covering the spectrum from the UV to the far infrared with sufficient spectral resolution to create accurate filtered radiances and spectral radiances of the various space-borne narrowband sensors and spectrometers in orbit on various platforms. It also carries two broadband radiometers, one to measure the total radiance and the second to measure shortwave radiances, 0.2-3.5 μm, so as to serve as a calibration standard for Earth Radiation Budget Sensors. As radiometrically accurate radiances are the starting point for long term climate records, the panel recommends the development and deployment of the RCTRO early in the NPOESS era.

Highly accurate measurements of solar irradiances along with the energy budget of the Earth represent fundamental climate variables that have revealed considerable information concerning the workings of the climate system and through the extension of the record of accurate measurements into the NPOESS era, should lead to constraints on radiative forcing and climate sensitivity. Given the threat of a gap in the highly accurate multi-decade record of Earth radiation budget measurements, the panel also recommends that the CERES FM-5, now awaiting launch on NPOESS C-1, be refurbished and flown on NPP. In addition, a copy of SIM should be added to the NPP or the Glory payloads so as to continue the UV to near IR solar spectral irradiances started with SORCE. This recommendation also calls for the development of the NPOESS ERB Sensor along with TSIS for launch on NPOESS C-1 and C-3. Ultimately, the long-term success of all climate measurements requires a more robust approach to continuity than is provided by our current reliance on overlapping measurements.

CLIMATE MISSION 2 TABLES

Science and application capabilities: RCTRO

Key Science Question	Measurement	Instruments
How are accurate long term records of atmospheric and surface properties to be developed?	Calibrated Radiances and overlapping measurements of broadband and narrowband radiances from multiple sensors	Shortwave spectrometer Thermal infrared spectrometer Broadband active cavity radiometer Filtered broadband active cavity radiometer GPS receiver
How are atmospheric temperatures, pressure, geopotential height fields and water vapor changing?	Radio occultations	GPS

Instruments and science objectives: RCTRO

Instrument	Radiation Budget, and radiance calibration for long term atmospheric and surface properties	Temperature, pressure and water vapor	Estimates of climate sensitivity
Shortwave spectrometer	Primary	NA	Primary
Thermal infrared spectrometer	Primary	Primary	Primary
Broadband active cavity radiometer	Primary	NA	Primary
Filtered broadband active cavity radiometer	Primary	NA	Primary
GPS	NA	Primary	Primary
GPS Radio Occultation on NASA and NPOESS	NA	Primary	Primary

Instrument requirements: RCTRO

Instrument	Requirements	Comments
	Orbit	3 satellites: 2 in precessing orbits separated by six hours of crossing time, and 1 ready to launch.
Shortwave Spectrometer		(0.2-3 μm) with a nadir field of view ~ 100 km, steerable to achieve various view angles.
Thermal infrared spectrometer		(3-100 μm) with a nadir field of view ~ 100 km, steerable to achieve various view angles
Broadband active cavity radiometer		(0.2-100 μm) with a nadir field of view ~ 500 km Steerable to achieve various view angles
Filtered broadband active cavity radiometer		(0.2-3 μm) broadband shortwave radiances with a nadir field of view ~ 500 km Steerable to achieve various view angles
GPS receiver		High precision, high stability oscillator
GPS satellites		With high accuracy ultra stable oscillator Radio occultation receivers that can receive GPS, GLONASS and Galileo radio signals

Science and application capabilities: ERBS Continuation

Key Science Question	Measurement	Instruments
How is the Earth's radiation budget and cloud radiative forcing changing?	Radiances	CERES Flight Model- 5 scanning radiometer and ERBS follow-ons
		SIM TSIS follow-ons
How can we improve estimates of global-scale climate sensitivity?	Overlapping measurements of broadband radiances from multiple sensors	CERES Flight Model- 5 scanning radiometer and ERBS follow-on
		SIM TSIS follow-ons

Instruments and science objectives: ERBS Continuation

Instrument	Radiation Budget	Estimates of climate sensitivity
Scanning Radiometer	Primary	Primary
SIM	Primary	Primary

Instrument requirements: ERBS Continuation

Instrument	Requirements	Comments
	Orbit	Fly on NPP, 1:30 orbit. Requires VIIRS for scene identification ERBS follow-ons on NPOESS C-1 and C-3
Scanning Radiometers	Modified CERES Flight Model-5	Change mirror attenuator to improve on orbit solar calibrations Replace CERES narrow 8 to 12 μm window filter (one of 3 CERES channels) with the ERBE longwave filter
Spectral Irradiance Monitor		Fly on NPP or Glory. Requires solar pointing platform TSIS follow-ons on NPOESS C-1 and C-3

Climate Mission 3: Ice Dynamics

Mission Summary – Ice Dynamics	
Variables	Ice sheet surface velocities; Estimate of ice sheet sensitivity
Sensor(s)	InSAR
Orbit/Coverage	LEO, global
Panel Synergies	Solid Earth, Water

Changes that have occurred in the Arctic over the past few decades include reductions of sea ice thickness and extent, reductions in the length of the sea ice season throughout much of the marginal sea ice zone, lengthening of the seasonal melt period with associated increases in open water, retreat of mountain glaciers, and increased melt and loss of ice around the margins of the Greenland ice sheet. Changes in the Antarctic have included, most importantly, ice shelf retreat, which can lessen or eliminate the buttressing effect of the ice shelves, without which the upstream grounded ice can accelerate its seaward motion and flow into the ocean, contributing further to sea level rise. The controls on ice flow are the subject of active investigation and debate due to critical observational and theoretical gaps about the dynamics of large ice sheets. The snow and ice changes have important consequences for the rest of the climate system. Growing evidence suggests that climate changes can be abrupt (NRC, 2002). Ice core results suggest that major changes can occur on much shorter time scales than previously believed possible. Recent satellite observations suggest that sectors of the Greenland ice sheet can abruptly speed and thin over periods of just a few years. These changes in polar climate could eventually have severe impacts world-wide, through sea level rise and changes in ocean circulation. Finally, many of these processes are absent from current ice-sheet models and many current global climate models (GCMs) fail to include active ice sheets at all, suggesting that an important and variable component of the Earth System is being overlooked in climate prediction.

Key scientific goals of Climate Mission 3 are to: (1) Understand glaciers and ice sheets sufficiently to estimate their contribution to local hydrology and global sea level rise and to predict their response to anticipated changes in climate, (2) Understand sea ice sufficiently to predict its response to, and influence on, global climate change and biological processes, (3) Measure how much water is stored as seasonal snow and its variability, and (4) Understand the interactions between the changing polar atmosphere and the changes in sea ice, snow extent, and surface melting.

To address these goals, key measurement objectives include: ice and snow distributions, topography and surface elevation, ice sheet mass, ice deformation, accumulation and melt, surface temperature, characterization of ice and snow types, and ice and snow thicknesses.

For climate studies, one of the most important needs is for continuation of the climate records and analyses of several extremely important climate variables that are already being monitored and which should be monitored routinely throughout the period covered by the Decadal Survey and beyond. These variables include sea surface temperatures and Arctic and Antarctic sea ice concentrations and extents, the latter being well-measured by satellite passive-microwave observations since the late 1970s. As stated previously, these measurements are currently in jeopardy in the NPOESS effort by the proposed elimination of CMIS until a re-bid instrument is available for C-2. The importance of maintaining these measurements cannot be overstated.

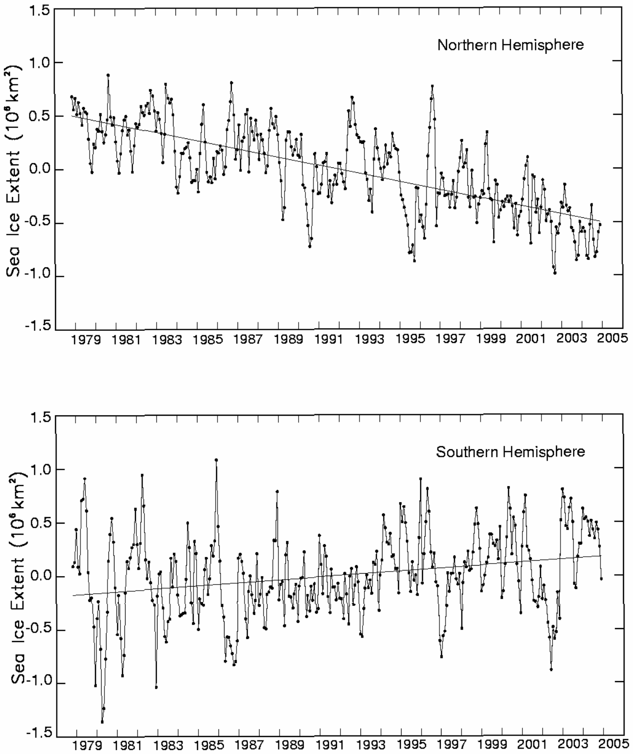

FIGURE 9.6. Monthly sea ice extent deviations in the Northern and Southern Hemispheres from November 1978 through December 2004, derived from satellite passive-microwave observations. The Arctic sea ice decreases are statistically significant, with a trend line slope of -38,200 ± 2,000 km^2/yr, and have contributed to much concern about the warming Arctic climate and the potential impacts on the Arctic ecosystem. The Antarctic sea ice increases are also statistically significant, although at a much lesser rate, +13,600 ± 2,900 km^2/yr. The Northern Hemisphere plot is extended from Parkinson et al. (1999), and the Southern Hemisphere plot is extended from Zwally et al. (2002).

Current plans lack instruments to obtain fine resolution (meters), to enable all weather coverage, and to measure surface motion of the ice. These measurements would complement the topography measurements of the Climate Mission 1 (Clouds, Aerosols and Ice Mission), which are excellent for obtaining ice elevation but are not ideal for measurements of ice dynamics. Ice dynamics, including the outward flow of ice in fast-moving ice streams, are critical for the discharge of ice from the ice sheet to ice shelves and/or to the ocean, and hence are critical for the societally important issue of ice-sheet-induced sea level rise.

We propose a mission aimed explicitly at ice dynamics, specifically a C-band left/right looking interferometric Synthetic Aperture Radar (InSAR) to be flown in polar orbit and with an orbit maintenance and satellite navigation sufficient for SAR interferometry. The orbit repeat must be short enough to achieve coherence between repeat pass observations but long enough to insure total geographic coverage. C-band is selected based on the heritage of highly successful measurements made using the ERS-1/2, RADARSAT, and Envisat SARs over ice. Lower frequency systems, such as L-band as used on the Japanese ALOS, are also likely to provide important image and interferometric data for cryospheric research. However, deeper penetration of the signal into the low-loss upper portions of the ice sheet will be a challenge for L-band instruments because of the consequent decrease in coherence, which is already low for many parts of Antarctica even at C-band. This challenge can potentially be addressed by stringent requirements on orbit repeat cycles and repeat orbit baselines.

RFI responses relevant to this proposed mission include InSAR Applications for Exploration of the Earth (see RFIs from the InSAR Steering Group and Andrew Gerber). InSAR will provide observations of ice sheet surface velocity which, through the ice flow law, will yield estimates of the stresses acting on the ice sheet. Such information is critically important for understanding the forces presently controlling ice sheet flow (side drag versus basal drag on ice streams, for example), and for predicting changes in ice sheet flow due to changes in climate (for example, motion acceleration driven by increasing surface melt water drainage, which leads to greater lubrication at the glacier bed in the marginal regions of the Greenland ice sheet). This is precisely the information most necessary for understanding ice sheet processes sufficiently to capture their behavior in global climate models.

SAR as an imaging tool also provides information on the sea ice deformation field; and some analysis suggests that SAR data might be useful for updating algorithms of sea ice concentration and extent. Furthermore, in addition to its value for ice sheet dynamics and sea ice, an InSAR instrument, with suitable choice of operating frequencies, would have significant benefits for the solid Earth and natural hazards communities (see Solid Earth Panel and Applications Panel chapters).

The InSAR mission would be greatly strengthened through coordination or addition of other missions. Two are particularly significant:

- Ideally, InSAR should be flown in coordination with the Climate Mission 1 (Cloud, Aerosols and Ice) or other spacecraft carrying laser/radar altimeters for snow/ice surface elevation. The altimeter provides highly accurate topographic measurements along narrow swaths while the InSAR can provided coarser estimates of topography in two dimensions.
- InSAR measurements of ice motion and topography combined with highly accurate elevations from Climate Mission 1 (Cloud, Aerosols and Ice) and with gravity measurements from a GRACE-type mission would yield much improved estimates of changes in ice sheet mass balance. The combination of measurements of ice sheet motion, topography and mass would yield a powerful tool for assessing changes in the ice sheets. GRACE also has significant applications for the oceanographic and hydrologic communities. A GRACE-type follow on mission should be seriously considered as a component of Climate Mission 3 (Ice Dynamics).

CLIMATE MISSION 3: TABLES

Science and application capabilities

Science Goal	Measurement	Instruments
What is the response of the ice sheets to climate change? How can we improve the incorporation of ice sheets in climate models?	Fine resolution measurement of surface motion of the ice and ice elevation	InSAR Climate Mission 1 (altimetric lidar) GRACE Follow-on
How can we better estimate the contribution of ice sheets to sea level change?	Fine resolution measurement of surface motion, repeat measurements of topography, changes in gravitational field	InSAR Climate Mission 1 GRACE
What is the interaction between sea ice, climate and biological processes?	Sea ice distribution and extent Snow cover on sea ice Sea ice motion Sea ice freeboard SST Ocean color	SAR Climate Mission 1 (altimetric lidar) EOS AMSR-E SSMI MODIS NPOESS
What are the short term interactions between the changing polar atmosphere and changes in sea ice, snow extent and surface melting?	Sea ice distribution and extent Snow cover and melt onset Sea ice Motion	SAR Climate Mission 1 (altimetric lidar) EOS AMSR-E SSMI MODIS NPOESS

Instruments and science objectives

Instrument	Ice sheet surface velocities	Estimates of ice sheet sensitivity
InSAR	Primary	Primary

Instrument requirements

Instrument	Requirements	Comments
InSAR	Left/Right looking (3-D)	Three-dimensional vector displacements are achieved by having at least 3 views of a given scene, which requires that the InSAR be able to look both to the left and to the right on both ascending and descending orbits (this actually gives 4 views, so there is some redundancy).
	Polar orbit	Orbit maintenance and satellite navigation sufficient for SAR interferometry. Orbit repeat short enough to achieve coherence between repeat pass observations but long enough to insure total geographic coverage.
	C-band	Demonstrated coherence over ice

Climate Mission 4. Measuring Ocean Circulation, Ocean Heat Storage, and Ocean Climate Forcing

Mission Summary – Ocean Circulation, Heat Storage, and Climate Forcing	
Variables	Surface ocean circulation; Bottom topography; Ocean-atmosphere interaction; Sea level
Sensor(s)	Swath radar altimeter, Scatterometer
Orbit/Coverage	LEO, global
Panel Synergies	Solid Earth, Water, Weather

Ocean altimetry measurements monitor changes in sea level. Changes in mean sea level have several components, of which the two major ones are thermal expansion of a warming ocean and transfer of land ice to the oceans (from melting, calving, or ice flow into ice shelves). Measuring the former is of extreme importance because it is a sensitive measure of how rapidly heat is being mixed into the ocean and is a key factor in the rate of global warming. Altimetric measurements can improve our knowledge of heat uptake (Willis et al., 2004) by supplementing measurements of the bulk ocean temperatures heretofore measurable only by ships or buoys (i.e., not just sea surface temperature that is measurable by satellite). Indeed the recent analysis of Forest et al. (2006) suggests that the current climate models are overestimating the heat uptake. Combining altimetry with the mass measurements of a GRACE instrument allows the separation of the thermal and fresh-water/ice components of sea level rise. On a finer scale, the gradients of the measured difference between surface topography and the geoid are a measure of circulation at the surface of the ocean. For example, Goni and Trinanes (2003) showed that hurricanes gain energy as they pass over the Gulf of Mexico Loop Current and that the position of the Loop Current can be effectively tracked from multi-altimeter measurements of sea level elevation. This information can be utilized to improve forecasts of hurricane strength and thus can save lives.

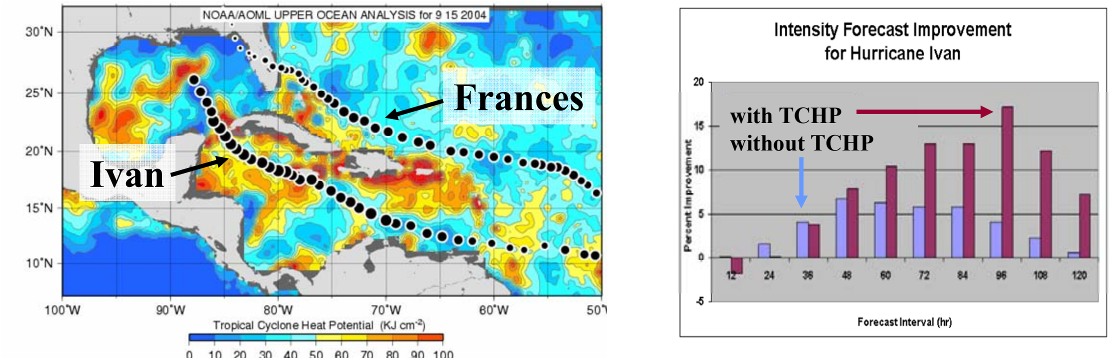

FIGURE 9.7 Use of altimetric sea surface height, calibrated to upper ocean heat content or 'hurricane potential,' would have provided 17% improvement in the 96 hour forecast of Hurricane Ivan intensity. The map and plot shows the tropical cyclone heat potential field (TCHP, upper ocean heat content from the sea surface to the depth of the 26 ^{o}C isotherm) estimated using altimeter-derived sea height anomalies, sea surface temperature and climatology of the temperature and salinity fields within a two-layer reduced gravity approximation. (Courtesy G. Goni and M. DeMaria/NOAA)

Ocean surface topography has been measured continuously since 1992 using nadir-pointing altimeters operated by NASA and CNES (TOPEX/Poseidon, Jason) and by the European Space Agency (ERS-1, ERS-2, Envisat). Climate Mission 4 is proposed as a 5 year satellite mission using a wide-swath radar altimeter to measure ocean surface topography globally (or at least throughout the non-ice-covered oceans, depending on the selected orbit; see discussion below) with minimal or no spatial gaps. The wide-swath technology is capable of both continuing the climatically important sea level elevation time series in a consistent manner and also mapping mesoscale eddies globally every few days. A wide-swath altimeter was originally planned as part of the Jason-2 altimeter, and revival of a wide swath was endorsed in the NRC decadal survey interim report (2005). Wide-swath technology has undergone considerable development (Fu and Rodriguez, 2004), and the design currently under discussion (Hydrosphere Mapper RFI; Water RFI) provides high resolution spatial coverage throughout the swath. It will fulfill our vision both by offering an extension of the existing long-term altimetric time series of global sea level and by providing essential observations to allow a process study of the role of eddies in upper ocean processes.

At present NASA (U.S.) and CNES (France) jointly fly one radar altimeter, Jason, and have plans for a follow-on mission. ESA flies a second altimeter on Envisat, in a different orbit, and has plans for a continued program. The U.S. Navy runs a third altimeter, GFO. France and India have also announced plans to launch an altimeter. Measurements from these instruments are mapped jointly to provide a best estimate of sea level. Nevertheless, there are many oceanic features that simply cannot be seen without a wide-swath altimeter, such as eddies and the warm ocean currents that amplify hurricanes. Laser altimeters do not meet the oceanographic requirements, because they do not provide data in cloudy regions. No space program has current plans for a wide-swath radar altimeter, and such measurements are needed to quantify the ocean’s role in climate change.

Climate Mission 4 with wide-swath altimetry will substantially augment the current and planned ocean satellite missions. It alone can provide a detailed picture of mesoscale circulation that can be used to improve our understanding of the physics governing ocean circulation and of the interactions between the ocean and atmosphere. This improved understanding will lay the groundwork for improvements in predictive climate models and will serve as a benchmark record of current ocean circulation against which future changes in ocean circulation can be judged.

Wide-swath altimeter programs have potential payoffs outside the purview of the ESAS Climate Change and Variability Panel both for hydrologic and geophysical applications. The hydrologic community has identified wide-swath altimetry as a means to monitor lake and river levels on a regular basis, particularly at high latitudes. To the extent that the global hydrologic cycle is part of the climate system, this would have clear payoffs for climate research. The geophysical community has advocated high-precision wide-swath altimetry as a means to measure the high wavenumber geoid gradient, which provides a measure of sea floor bathymetry and correspondingly, of bottom roughness. This information also has potential climate benefits, because it will improve the representations of the bottom boundary condition and of topography-driven mixing processes in ocean general circulation models.

The different potential user communities for a wide-swath altimeter have advocated different orbit requirements. Oceanographic users would prefer an orbit that was not sun synchronous and that was optimized to avoid aliasing any of the major tidal constituents into low frequencies. Geophysical users favor an orbit that would provide complete global coverage in ice-free regions, with no requirement for repeat tracks (see “ABYSS-Lite” RFI response). Hydrologic users have advocated an 8 day sampling interval to be achieved with a 16 day repeat orbit, and although they have proposed a sun synchronous satellite to reduce mission costs, the choice of a sun synchronous orbit is not critical to the hydrologic science objectives (see “Water” RFI response). In order to select an orbit that best satisfies all user requirements, NASA needs to assess the design requirements for a non-sun-synchronous orbit and to evaluate tidal aliasing patterns associated with possible orbits.

Wide-Swath Altimeter Measurements would be enhanced if the data were coincident with measurements from a gravity mission (“GRACE Follow-On” RFI response). An altimeter alone measures sea surface height anomalies associated with geostrophic flows in the ocean, but it cannot detect mean absolute dynamic topography associated with the mean geostrophic circulation. Independent gravity data provide a large-scale geoid, allowing absolute geostrophic velocities to be determined. A gravity mission tracks time-varying changes in ocean mass that are also useful for identifying whether sea level changes are due to ice melt, thermal expansion of the ocean, or mass displacements within the ocean.

Since the upper ocean circulation is wind-driven, Climate Mission 4 includes coincident global high-accuracy measurements of ocean vector winds at daily or twice-daily frequencies. Long-term plans in the U.S. have focused on passive microwave wind measurements that have not been able to provide accurate wind estimates at high or low speeds. Wind forcing can be estimated by active microwave measurements of sea-surface roughness. Active scatterometry measurements have been made on and off since the launch of ERS-1 in 1992. Currently, the U.S. flies one scatterometer, QuikSCAT, which is roughly able to meet the data coverage requirement. ESA recently launched ASCAT, which has a relatively narrow field of view that will not fully capture high-frequency temporal variability in the winds that drive the ocean circulation. No plans exist currently to ensure coincident wind and sea surface height measurements.

At this stage, the combination of a wide-swath altimeter and complementary scatterometer would provide a research mission with immediate payoffs by advancing our understanding of the physics driving the upper ocean. These payoffs could well lead to advances in the representation of upper ocean processes in climate models as well as better ENSO forecasts. The scientific user community will likely request continuous measurements as an operational program, assuming that the wide-swath mission meets its objectives.

CLIMATE MISSION 4: TABLES

Science and applications capabilities

Key Science Question	Measurement	Instruments
How is ocean surface topography changing?	Sea surface height	Swath Radar Altimeter
What is the role of ocean eddies in upper ocean processes?	Sea surface height Ocean vector winds	Swath Radar Altimeter Scatterometer
How can knowledge of the mesoscale ocean circulation and ocean bottom topography be utilized to improve ocean circulation models and our understanding of ocean-atmosphere interaction?	Sea surface height Ocean vector winds	Swath Radar Altimeter Scatterometer GRACE-type follow-on
How is sea level changing?	Sea surface height Upper ocean temperatures	Swath Radar Altimeter GRACE-type follow-on

Instruments and science objectives

Instrument	Surface ocean circulation	Bottom topography	Ocean-atmosphere interaction	Sea Level
Swath Radar Altimeter	Primary	Primary	Primary	Secondary
Scatterometer	Primary	NA	Primary	Secondary

Instrument requirements

Instrument	Requirements	Comments
Swath Radar Altimeter	Orbit	Assess requirements for a non-sun synchronous orbit and to evaluate tidal aliasing to best meet the needs of oceanographic, geophysical and hydrologic users.
	Coverage	Global (or near global) with minimal or no spatial gaps
Scatterometer	Orbit	Coincident with Altimeter
	Coverage	Twice daily frequencies

High Priority Areas Requiring Innovative Approaches

Some of the major issues in climate research require innovative measurement approaches beyond the RFI responses and beyond those required for Missions 1-4. Focus areas Alpha and Beta are designed to highlight new satellite observations and approaches with the potential to greatly expand our knowledge of the climate system, test key climate processes in the models, and improve our ability to forecast climate variability and climate change. These potential missions require innovative measurement approaches beyond the RFI responses and beyond those required for Missions 1-4. Because of the extent to which these missions require innovative thinking and investment in new technologies, specific instruments and plans are not included.

Focus Area Alpha: Measurement of Surface Fluxes

Climate prediction depends on understanding the exchanges of heat, water, gases, and momentum between the ocean, atmosphere, land, and cryosphere. These exchange fluxes are currently measured at heavily instrumented surface sites. They are not readily measured from space. Without space-based observations, we lack a global perspective on spatial and temporal variations in air-sea and land-atmosphere fluxes and thereby lack the information needed for reliable climate predictions.

Improving surface flux estimates is a difficult challenge. Although many of the responses to the ESAS Request for Information (RFI) mentioned fluxes, none had a primary objective of obtaining improved surface flux measurements, likely because no simple suite of space-borne instruments will provide direct measurements of all desired surface fluxes. NASA, NOAA, and other agencies should pursue a multi-step approach in order to improve surface fluxes. This may include a broad range of activities such as evaluating existing observations, improving data assimilation schemes, expanding the surface-based observing system, and developing new satellite sensors.

Different surface fluxes have different measurement requirements. For example, current research (Curry et al., 2004) shows that the air-sea flux of sensible heat can be parameterized as a function of surface wind, sea surface temperature, and near surface air temperature. Thus a potential satellite mission might combine active microwave scatterometer winds, passive microwave sea surface temperature, and boundary layer atmospheric temperatures. Latent heat fluxes would require the same quantities as sensible heat fluxes as well as an estimate of boundary layer humidity. Detecting small temperature differences between the surface and the lower atmosphere is particularly challenging and is likely to test the capabilities of atmospheric sounders. Moreover, the bulk parameterizations may not be accurate, and the satellite mission may need to find a more direct measurement of the fluxes. Some progress is being made along these lines for momentum fluxes, using scatterometer winds, but no obvious strategies exist for other surface fluxes.

Not all flux-related variables may be measurable from space at present. However, current technology does allow satellite measurement of many key parameters such as winds, sea surface temperatures, salinity, soil moisture, atmospheric water vapor, and rain. Thus, we recommend a detailed study of whether parameteric-based flux measurements using current or anticipated technologies would provide the accuracy needed for air-sea or air-land fluxes. The technological challenges involved in detecting fluxes from space should not justify inaction.

Focus Area Beta—Measurement of Convective Transports

Atmospheric convection is a key process in climate models that is not well understood. Convection transports heat, water vapor, momentum, trace gases, and aerosols in the presence of clouds and mixed phases of precipitation. Convection links the near-surface boundary layer with the upper reaches of the troposphere and controls the stratosphere-troposphere exchange of gases.

Convection is a fundamental process that is treated only parametrically in climate models as a vertical redistribution of heat, momentum, and water vapor. Changes in upper tropospheric water vapor constitute a prime feedback in a warming climate, and thus understanding how convection controls the distribution of water vapor will advance climate modeling. Convective transport is complex, involving both upward and downward fluxes within the same air column. The scale of these motions and their coincidence with clouds makes direct measurement of air-mass or tracer-mass fluxes not practical from space. The interaction of clouds and precipitation with soluble species or trapped aerosols makes convective transport generally non-conservative. Improved modeling of convection is one of the key advances needed for regional climate predictions.

Trace Gases and Aerosols

Improved knowledge of the effects of convection is needed both for predicting the abundance of greenhouse gases and other pollutants and for identifying primary emissions. The rate of vertical mixing in the atmosphere controls the abundance and impact of many short-lived and reactive chemical species—both gases and aerosols. The photochemical environment of the boundary layer, where most such species are emitted, is very different than that of the free troposphere. For example, pollutants trapped in the boundary layer are often chemically processed and scavenged from the atmosphere near their sources, whereas once lofted into the free troposphere, these same species can travel around the globe generating intercontinental pollution. Even for gases with little chemical reactivity, such as CO_2 and ^{85}Kr, the rate of vertical mixing in the atmosphere controls the gradients between surface sources and the remote atmosphere, and these gradients are used to infer the location and magnitude of sources. Important vertical transports occur both through large-scale adiabatic lifting motions (reasonably well represented in models) and through convective motions, including clouds and turbulence, which are not well understood nor well represented in atmospheric tracer transport.

Stratosphere-Troposphere Exchange (STE)

The balance between convection and radiation controls the tropical tropopause region, and thus it plays a major role in stratosphere-troposphere exchange, particularly the abundances of water vapor, aerosols, and halogen compounds entering the stratosphere in the tropics. Convection also contributes to erosion of the mid-latitude tropopause in spring and the ensuing flux of ozone into the troposphere from above. One objective is to measure atmospheric composition through the upper troposphere and across the tropopause to help understand the atmospheric regions and processes involved in STE.

The observations that are needed are those that (1) characterize the convective event (e.g., enable the derivatives of the large scale convergence of heat and water vapor, cloud base and top, precipitation) and (2) measure the redistribution of trace species, including water isotopes, to derive the net convective transports. For example, missions might be designed to accumulate the statistics of convection, building up the patterns of trace species before and after convective transport along with the magnitude/type of convective transport. Measurements taken during the airborne CRYSTAL-FACE experiments are able to follow specific events and measure the altitude of convective outflow along with the abundance of boundary layer tracers and obtain needed measurements.

A mission focused on convection cannot at this time be assembled from known instruments (or directly from RFI responses). However, the components might include: (1) a limb-scanning instrument with high vertical resolution (1 km) and sensitivity to trace species and water isotopes; (2) a lidar or similar measurement of boundary layer pollutants, such as CO or aerosols; (3) cloud measurements and imager; and (4) a precipitation measure. Given the diurnal cycles in convection and rainfall, the observations cannot be made usefully from a sun-synchronous orbit. The most important convective transports occur in the tropics or mid-latitudes and could be served by a diurnally shifting low-inclination LEO like TRMM. Further, these measurements would be greatly enhanced by a cloud-aerosol mission (such as Climate Mission 1). The auxiliary use of a GEO pollution or storm mapper might help to fill in the full cycle of convection. As noted earlier some intensive *in situ* campaigns are required to more fully understand the convective cycle.

OTHER SPECIAL ISSUES

The quality of spaced-based measurements of the Earth system that will be collected in the next two decades will provide scientists with a unique opportunity to gauge climate trends both in terms of the mean state of the system and its variability, including probability of extreme events (Climate Missions 1-4). The possibility of investigating processes (Focus Areas Alpha and Beta) that can improve modeling efforts has the potential to advance climate forecasts significantly and to produce models that will be ever more useful for regional impact studies.

However, providing the type of information necessary for detection of climate variability and change requires coordination of instruments, missions, and analysis programs. The realization of the program is also dependent on several major issues involving interagency collaboration and international cooperation. The transition of science-driven missions to operational missions presents challenges related to the integrity of the scientific data. The problems of data continuity, relative and absolute calibration of the measurement sequence, open access and availability of the data, standardization of the processing and distribution standards must all be considered.

Interagency Issues

A number of institutional challenges must be addressed in order to achieve the full potential of the climate missions outlined above. It is necessary to identify clearly the respective roles of NASA, NOAA, NSF, DOE, DOD, and other agencies in advancing sensor technology, system calibration and validation, and data archiving and management.

Presently, NOAA's plans for data calibration after the NPOESS Preparatory Project (NPP) fall short of those required for climate studies due to budgetary constraints, as well as to institutional culture. Other issues related to transparency of the processing methodology are issues of current concern. Given the national commitment to NPOESS, and current problems with it as a suitable and cost-effective platform for climate studies, NOAA, NASA, and other agencies with climate interests should actively participate in a plan to insure adequate long-term, quality data sets for climate. A number of recommendations related to these issues can be found in previous NRC reports (e.g., NRC 2000a, NRC 2000b, NRC 2000d). In order for NOAA to realize its mandate as the federal agency charged with collecting and managing space-based observations for climate, NOAA must have the necessary funding to acquire the infrastructure and workforce, and must embrace a culture in which climate is a priority. This will require a plan whereby research and operations responsibilities are integrated in order to balance technical innovation, data quality and stability, and flexibility to meet emerging science questions and concerns.

International Partnerships

International partnering on instrument development, satellite operations, data exchange and data analysis spreads the cost burden, mitigates risks to gaps in particular data streams, encourages technical innovation by broadening the engineering expertise base, and increases the number of science users. NASA and its international partners have enjoyed these benefits through numerous programs including joint ventures on EOS, TOPEX/Poseidon and RADARSAT-1 and more generally through programs such as the International Global Observing System, the International Polar Year, and CLIVAR. Moreover it is now relatively common for flight agencies to offer announcements of opportunity to the international science community as the agencies attempt to maximize the payoff of each flight project.

While the potential advantages of collaborations are obvious, realizing the advantages can be complicated by a number of factors. Instruments built by one partner may not be designed to the exact requirements of another partner and technology transfer restrictions may prevent the exchange of important technical details about the instruments. Restrictions on access to data and software vary from country to country, as do approaches to calibration and validation. Joint ventures between government flight agencies and commercial partners can result in serious complications with data cost, availability, and distribution. With this in mind, international partnerships should only be fostered where synergy between instrument capabilities and the science requirements is strong, where there is free and easy access to data, and where there is transparency in the process of analyzing data such that analysis algorithms are freely available.

Improving Climate Modeling Through the Application of New Satellite Measurements

Interaction between the climate modeling and satellite remote sensing communities is limited (NRC, 2001a). Existing data sets are underutilized by the climate modeling community. The CLIVAR Climate Process Teams Program for *in situ* measurements is designed specifically to understand processes poorly handled by the climate models and provides a framework that could be adopted for a similar effort involving satellite measurements. We recommend a new cross-agency effort to foster a more fertile cross-over between those collecting, managing, and analyzing satellite observations and the modeling groups. Such a program must be well-managed and funded. Success will require improved, coincident *in situ* observations such as those traditionally carried out by DOE, DOD, NSF, and other agencies, but these should be augmented to include dedicated field programs, that address specific scientific questions related to the proposed missions.

Workforce

A successful and robust plan for improving climate prediction must include plans for the education of the workforce, including the engineers who design sensor systems and the geoscientists who interpret data. A close interaction between these groups to assess the evolving needs is essential. A concerted effort should be made to fund universities and national labs for training graduate students and post-doctoral researchers for this purpose.

Data Management and Distribution

A successful climate science program will require a robust data system for satellite measurements as outlined in previous NRC reports (NRC, 2000b; NRC, 2004, NRC, 2005). In particular, computer systems must be designed to facilitate reprocessing, archiving, and distribution of NPOESS data. Many of the recommendations made in a recent NRC report (NRC, 2004) apply to satellite-based observation. Three points deserve particular attention: First, there should be easy to data. Second, metadata should be available to document sensor performance history and data processing algorithms, and to allow reprocessing to adjust for bias, drift, and other errors present in the data sets. Third, representatives from various members of the climate community should be actively involved in data generation and stewardship decisions. These procedures will enhance and expand data access by researchers and climate service providers and foster the development of value-added products for the Climate Services discussed earlier.

TABLE 9.2 Status of major climate variables and forcing factors. Variables identified in the GCOS 2nd Adequacy Report as largely dependent on satellite observations are indicated in red. The list of RFIs can be found in Appendix E

Measurement (GCOS table)	**Strategy**	**Current Status**	**Follow-on (2010-2020)**	**RFI**
Total Solar Irradiance (1.2)	Direct measurement	SORCE launched 2003; GLORY (TIM only) 2008	NPOESS TSIS--GFE	47, 25, 30, 52
Earth radiation budget	***Multispectral Imagery Combined with Broadband Radiometers*** Scene identification, top of the atmosphere fluxes.	MODIS/CERES on Terra (2000) and Aqua (2002)	VIIRS/ERBS on NPOESS, C1 (2013) Mission 2	9, 17, 18, 25, 30, 52, 59, 76,
Surface radiation budget	***Multispectral Imagery Combined with Broadband Radiometers*** Scene identification, top of the atmosphere fluxes, and radiative transfer modeling	MODIS/CERES on Terra (2000) and Aqua (2002)	VIIRS/ERBS on NPOESS, C1 (2013) Mission 2	
	Surface-based radiometers ARM, BSRN, CMDL, SURFRAD sites, sparsely located			
Tropospheric Aerosols (1.3): geographic and vertical distribution of aerosols, optical depth, size, shape, and single-scattering albedo	***Multispectral imagers*** Provide optical depth and some inference of size over oceans and dark surfaces:	AVHRR since 1981 (NOAA 7) and currently on NOAA 16, 17, 18 VIRS on TRMM (1997) MODIS and MISR on Terra (2000); MODIS on Aqua (2002)	VIIRS follow-on to MODIS on NPP, NPOESS	35, 7, 25, 30, 52, 3, 77, 45, 61
	UV radiometer/imager Provide optical depth and some inference of absorption for elevated aerosol layers	OMI on AURA (2004) OMPS on NPP (2008)	OMPS on NPOESS Mission 1	
	Polarimeters Provide optical depth, size, shape, single-scattering albedo	POLDER on PARASOL (2005) APS on GLORY (2008) limited to the sub-satellite ground track	APS on NPOESS Mission 1	
	LIDAR Provide vertical profile of aerosol concentration and some inference of size and shape	CALIPSO (2006)	Mission 1	
	Surface Multispectral Radiometers Aerosol optical depth, size distribution. Single-scattering albedo for optically thick aerosols under completely cloud-free skies	AERONET, ARM	VIIRS on NPOESS Mission 1	
	Surface and Earth Broadband Flux Measurements Aerosol absorption under cloud-free conditions	CERES on Terra (2000) and Aqua (2004) combined with BSRN, ARM, SURFRAD sites	ERBS on NPOESS Mission 2	
Stratospheric Aerosol properties, optical depth, size, shape, and single-scattering albedo (1.3)	***Limb and Solar Occultation Measurements*** Profile of aerosol extinction	HIRDLS on Aura, infrared radiometer SAGE II on ERBS (1984-2006) SAGE III on Meteor (2002-2006) SciSat (Canadian-U.S)	***None***	63
	Limb Scattered Light Profile of aerosol optical depth		OMPS on NPP (2009) and NPOESS	
	LIDAR Vertical profile of aerosol concentration and some inference of size and shape	CALIPSO (2006)	Mission 1	3, 57, 110, 111

Measurement (GCOS table)	**Strategy**	**Current Status**	**Follow-on (2010-2020)**	**RFI**
Cloud properties (1.2): geographic and vertical distribution, water droplet effective radius, ice cloud crystal habitat and size, mixed-phase cloud water/ice ratio and hydrometeor size, and visible optical depth, cloud liquid and ice water amounts	***Multispectral Imagers*** Properties of single effective cloud layer.	AVHRR since 1981 (NOAA 7) and currently on NOAA-16, 17, and 18, inferences of hydrometeor size, but not phase. VIRS on TRMM; MODIS on Aqua and Terra provide inference of hydrometeor phase	VIIRS on NPP and NPOESS provides inference of hydrometeor phase	2, 110, 66, 111
	Multiple View Radiometers and Polarimeters	MISR on Terra, cloud altitude from stereo imaging POLDER on PARASOL, hydrometeor size and phase from polarimetry. APS on GLORY(2008), phase from polarimetry	APS on NPOESS, hydrometeor phase from polarimetry	
	15-μm Sounders and Imagers Cloud layer pressure for effective single-layered cloud system, even for optically thin cirrus	HIRS on NOAA-16, 17, 18 MODIS on Terra and Aqua AIRS on Aqua (2002) CrIS on NPP (2008)	CrIS on NPOESS	
	Microwave Imagers Microwave inference of cloud liquid water over oceans	SSMI on DMSP, TMI on TRMM, AMSR-E on Aqua	CMIS on NPOESS	
	LIDAR Upper boundary, extinction for optically thin clouds, and with polarization, particle phase	CALIPSO (2006)	Mission 1	
	Cloud Radar Cloud boundaries and vertical distribution of liquid water and rates of drizzle when precipitation is light	CloudSat (2006)	Mission 1	
Ozone: stratosphere and troposphere (1.3)	***UV Radiometer/Imager*** Provides tropospheric column ozone and coarse vertical resolution profiles of stratospheric ozone	OMI on Aura (2004)	OMPS Nadir on NPP (2009) OMPS Nadir on NPOESS	
	UV Limb Scanner provides vertical profile of stratospheric concentration	OMPS on NPP	OMPS Limb on NPP (2009) and NPOESS	
Trace gases controlling ozone (HCl, N_2O, CH_4, H_2O, HNO_3)	***Infrared Sounders*** Provides vertical profiles of tropospheric and stratospheric ozone	HIRDLS on Aura TES on Aura also provides limb viewing (not being used after 2005) AIRS on Aqua (2002)	***None***	61
	Microwave Limb Sounding Provides vertical profile of stratospheric ozone.	MLS on Aura	***None***	61
CO_2 (1.3)	***NIR Spectrometer*** High precision column concentrations of CO2.	OCO (2008). Goal is to achieve accuracies sufficient to allow determinations of sources and sinks. Surface-based networks (WMO GAW, NOAA, AGAGE).	***None***	3, 20
	Infrared Sounders	AIRS on Aqua (2002)	***None***	8
CH_4 (1.3)	***Infrared Spectrometer*** High precision column concentrations of CH4	TES on Aura Surface-based networks (WMO GAW, NOAA, AGAGE).	***None***	95
	Infrared Sounders	AIRS on Aqua (2002)	***None***	8

Measurement (GCOS table)	**Strategy**	**Current Status**	**Follow-on (2010-2020)**	**RFI**
Land surface cover and surface albedo (3) (snow cover, glaciers, ice caps covered later)..	***Multispectral imagery*** Vegetation index and inference of surface albedo	AVHRR on NOAA-16, 17, and 18: inferences of atmospherically corrected spectral albedos MODIS on Terra (2000) and Aqua (2002) Landsat series	VIIRS on NPP (2009) and on NPOESS	38
	Hyperspectral imagery Vegetation types and land cover	Hyperion (EO-1)	Mission 1	
Temperature (1.2): Vertical profiles	***Infrared and Microwave Sounders*** Vertical profiles of layer temperatures	HIRS/MSU since (1979) currently on NOAA-16, 17, and 18. SSM/I on DMSP (1995; 1997; 1999) AIRS/AMSU on Aqua (2002)	CrIS and ATMS on NPP (2009) and on NPOESS	8, 10, 5, 92, 43, 41, 48
	GPS Radio Occultation Vertical profiles with ~ 0.5-1 km resolution near the surface.	GPS on CHAMP (2000) and COSMIC (2007).	Mission 2	
Temperature (1.2): Vertical profiles (Cont'd)	***Surface Network*** Radiosonde temperature profiles WMO sonde network (1959)			
Water vapor (1.2): Column amounts and vertical profiles.	***Microwave Imaging*** Column water vapor amounts over oceans	SSM/I on DMSP polar satellites (1995; 1997; 1999)	ATMS on NPP (2009) and CMIS on NPOESS	
	Multispectral Imagery Column amounts from NIR water vapor channels	MODIS on Terra (2000) and Aqua (2002)	***No planned follow-on***	
	Infrared Sounders Water vapor layer amounts at relatively coarse vertical resolution in the troposphere	HIRS data from 1979 (TIROS-N). Currently on NOAA-16, 17, and 18.	CrIS on NPP (2009) and NPOESS	3, 92, 5, 8, 9, 10, 99
	High Spectral Resolution Infrared Radiometers Water vapor layer amounts at finer vertical resolution in the troposphere	AIRS on Aqua (2002) TES on Aura (2004)	CrIS on NPP (2009) and NPOESS	
	Infrared and Microwave Limb Scanning Radiometers Water vapor layer amounts in the upper troposphere and stratosphere	TES and MLS on Aura (2004)	***No planned follow-on***	
	GPS/Radio Occultation Profiles of temperature and water vapor with up to ~ 0.5 km vertical resolution near the surface.	CHAMP (2000) and COSMIC (2006)	Mission 2	
	Surface Network Radiosonde water vapor profiles WMO sonde network (1959)			
Fire disturbance (3)	***Near IR Thermal Imagery*** High spatial resolution detection of fire hot-spots.	AVHRR data from 1981 (NOAA-7). Currently on NOAA-16, 17, and 18. MODIS on Terra (2000) and Aqua (2002)	VIIRS on NPP(2009) and NPOESS	
Land biomass and fraction of photosynthetically active radiation (FAPAR) (3)	***Multispectral Imagery*** Index of vegetation and inference of FAPAR	AVHRR data from 1979 (NOAA-6) and currently on NOAA-16, 17, and 18. MODIS on Terra (2000) and Aqua (2002); Sea-WIFS	VIIRS on NPP (2009) and NPOESS Mission 1	
	Radar Land cover from C-band radar backscatter	Radarsat 1 (1995) and Radarsat 2 (2007), data commercially available	***No planned follow-on***	

Measurement (GCOS table)	**Strategy**	**Current Status**	**Follow-on (2010-2020)**	**RFI**
Glaciers, Sea Ice and Ice caps (3)	***Multispectral Imagery*** Area coverage.	AVHRR data from 1979 (TIROS-N). Currently on NOAA-16, 17, and 18. MODIS on Terra (2000) and Aqua(2002)	VIIRS on NPP (2009) and NPOESS	44, 111, 87
	Microwave Imagers Area coverage	SSM/I on DMSP (1995, 97, 99) AMSR-E on Aqua, TMI on TRMM (1997)	CMIS on NPOESS	
	Radars Ice area and flow, sea ice thickness from topography	Radarsat 1 (1995) and Radarsat 2 (2007) data commercially available.	Mission 3	
	LIDAR Ice elevation	GLAS on ICESat (2003)	Mission 1	
	Gravity Satellite Ice mass when combined with measure of topography.	GRACE (2002)	Grace follow on	
Permafrost and seasonally frozen ground (3)				
Snow cover (and snow water equivalent) (3)	***Radars combined with Microwave Radiometers*** Combination of area, roughness, and topography to provide snow water equivalent	Radarsat 1 (1995) and Radarsat 2 (2007) data commercially available	***No planned follow-on***	19, 10, 14, 56
Ground water (3)	***Microwave Imagers*** Soil moisture except for areas covered by ice/snow and heavily forested areas	SSM/I on DMSP (1995; 1997; 1999); AMSRE on Aqua (2002)	CMIS on NPOESS	96, 19
	Gravity Satellite Large-scale ground water (requires *in situ* auxiliary observations).	Grace (2003)	Grace follow on	
Lake levels (3)	***High Resolution Multispectral Imagery*** Lake areas	LANDSAT 7 (1999)	***LDCM***	
	Radars Lake area	Radarsat 1 (1995) and Radarsat 2 (2007) data commercially available	***No planned follow-on***	
	LIDAR Water surface elevation	GLAS on ICESat (2003)	Mission 1	
River discharge (3)	***High Resolution Imagery*** Lake and river areas	LANDSAT 7 (1999)	***LDCM***	
	LIDAR Altimeter River levels	ICESat (2002)	Mission 1	
	Radar Lake and river areas	Radarsat 1 (1995) and Radarsat 2 (2007), data commercially available	***No planned follow-on***	
Leaf area index (LAI) (3)	***Multispectral Imagers*** Vegetation index	AVHRR, data since 1981 (NOAA-6). Currently on NOAA-16, 17, and 18 MODIS on Terra (2000) and Aqua (2002), MISR on Terra (2000), Sea-Wifs (1997), VIIRS on NPP (2008)	VIIRS on NPOESS	
	High Spatial Resolution Multispectral Imagers Vegetation index at higher spatial resolution	LANDSAT 7 (1999) ASTER on Terra (2000) EO-1	LDCM Mission 1	
Sea Level	***Altimeter*** Ocean sea-level height	JASON 1 (2001) GFO	ALT on NPOESS Mission 4 Grace Follow-on	56

Measurement (GCOS table)	**Strategy**	**Current Status**	**Follow-on (2010-2020)**	**RFI**
	SAR Radars Area of coastal zones	Radarsat 1 (1995) and Radarsat 2 (2007), data commercially available	***No planned follow-on***	
Sea State (2.1), Surface Wind (1.1)	***Microwave Imagers*** Surface windspeed	SSM/I on DMSP (1995; 1997; 1999) AMSRE on Aqua (2002)	CMIS on NPOESS	98, 56
	Scatterometer Surface wind vector	QuikSCAT (1999) ASCAT on METEOP (?)	ASCAT (MetOp) Mission 4	
Ocean color (2.1)	***Multispectral Imagers with UV/blue capabilities*** Surface leaving radiances	SeaWifs (1997) MODIS on Terra (2000) and Aqua (2002)	VIIRS on NPP (2009) and NPOESS	86, 21 ,
Ocean surface (2.1) and sub-surface temperature (2.2)	***Multispectral Imagery*** Sea surface temperature	AVHRR, data since 1981 (NOAA-7). Currently on NOAA-16, 17, and 18 VIRS on TRMM (1997) MODIS on Terra (2000) and Aqua (2002)	VIIRS on NPP (2009) and NPOESS	
	Infrared/Microwave Sounders Sea surface temperature	AVHRR NOAA 16, 17, and 18 AIRS and AMSR-E on Aqua (2002) MODIS on Aqua (2002) and Terra (1999), MODIS	CrIS/ATMS on NPP (2009) + CMIS on NPOESS	
	Expendable Profiling Floats Profiles of temperature as well as temperature at depth of neutral buoyancy and surface.	ARGO floats		
Ocean surface (2.1) and sub-surface salinity (2.2)	***Microwave Radiometer and Scatterometer*** Surface salinity and ocean roughness		AQUARIUS (2010)	
	Expendable Profiling Floats Profiles of salinity as well as salinity at depth of neutral buoyancy.	ARGO floats		
Ocean surface (2.1) and sub-surface currents (2.2)	***Altimeter*** Ocean surface height from which currents derived	JASON 1 (2001)	ALT on NPOESS Mission 4	
	Gravity Satellite Subsurface or barotropic mass shifts (computed in conjuction with surface altimeter measurements)	GRACE (2002)	Grace Follow-on	
	Expendable Profiling Floats Position drift at depth of neutral buoyancy (and surface with some caveats).	ARGO floats		
Sub-surface Phytoplankton (2.2)				
Precipitation (1.1)	***Microwave Imagers*** Rainfall rate over oceans	SSM/I on DMSP (1995; 1997; 1999) TMI on TRMM (1997) AMSR-E on Aqua (2002)	CMIS on NPOESS; GPM (2012)	
	Precipitation Radar Vertical structure of rain rates	TRMM (1997)	GPM (2012)	
	Cloud Radar Rate for light drizzle	CloudSat (2006)	Mission 1	

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10
Weather Science and Applications

OVERVIEW

The dramatic improvement over the last few decades of numerical weather prediction (NWP) for forecast timescales of a day to a week or more has been a remarkable scientific achievement. Furthermore, weather and short-term climate changes associated with El Niño and La Niña events are now skillfully predicted several months in advance. These improvements were enabled by assimilation of observations into computer atmospheric models, which were improved through better scientific understanding of the atmosphere and related parts of the Earth system. The general public, decision-makers, and industry now depend on multi-day forecasts, and they are pressing for further improvements.

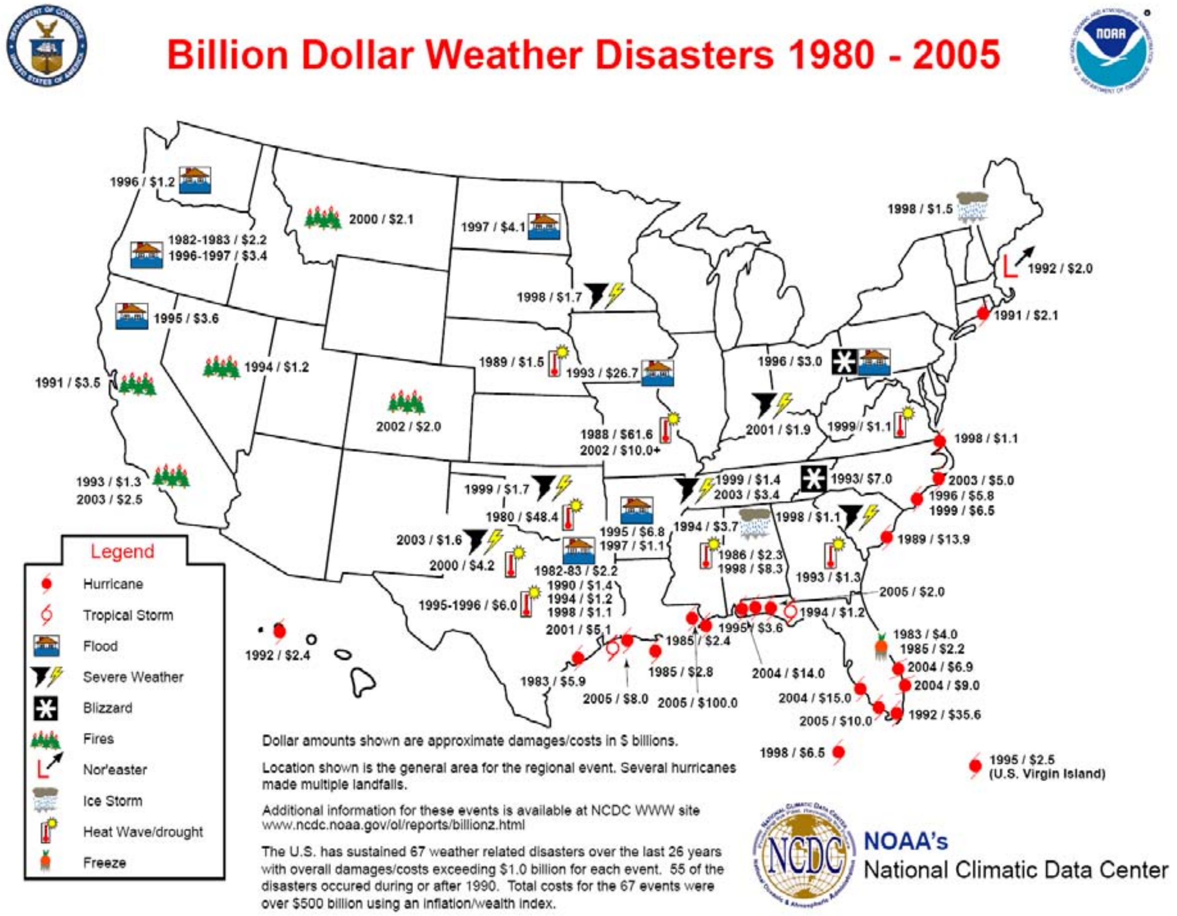
Further improved weather prediction requires observational and scientific improvements that provide major new prediction capabilities. Gaps in the observing system, our understanding of atmospheric processes, and our ability to optimally exploit observations in models must be filled. The growing global reliance on weather information places responsibility on NASA and the Earth science community to improve Earth science research and operational programs with new space-based and *in situ* observations. These observations can be used to answer key scientific questions and deliver operational products to provide improved economic and societal benefits. A balanced mix of proven, proof-of-concept, and new observing technologies are needed to enhance decision-making across many economic sectors, while also meeting the growing needs of improved forecasts for warnings and responses to extreme events.

Current successes have stimulated strong public and business demands for more and better products with finer temporal and spatial resolution. A significant component of the U.S. GDP (approximately $2-3 trillion) is directly or indirectly sensitive to weather and climate (NRC, 2003). The economic impact (Figure 10.1) can be felt in sectors such as natural resource management, energy, finance, insurance, real estate, services, retail and wholesale trade, manufacturing, transportation, civil engineering, and agriculture.

The growing demand for weather information has broadened in scope to require not only the traditional physical variables of the lower atmosphere, but also information about the land and sea surfaces, the chemical properties of the atmosphere, and the state of the near-space environment. While extreme events and associated human impacts attract the most attention, both the general public and economic decision-makers rely on the quality of everyday forecasts. For example, the development of renewable energy sources (e.g., wind, solar, biofuels) will require weather information to locate facilities as well as to manage the uncertainty associated with variability in natural resources. By 2025, use of a growing weather database will be as common as use of the GPS is today.

Improvements in weather prediction capabilities require increased accuracy, reliability, and duration of forecasts, with finer spatial and temporal detail, for a wider range of weather variables. These improvements will thus require an improved quality of satellite observations, effective assimilation of these observations into NWP models, and better interfaces between forecast products and user communities to deliver new suites of user-tailored forecasts. The value of added space-based observations will be greatly enhanced if new data are quickly made useful to the government, public and private sectors. This enhancement will require an enterprise-wide effort to dramatically shorten the current 20-year delay between the availability of research results and their transition into applications. In order to achieve fast infusion of technology into operations and decision-support, the effort will require improved communication and partnerships among the weather observation agencies, the university modeling community, and end users (NRC, 2000; 2003).

Achieving these results will require an integrated, vigorous, targeted program of research, technology development, measurements, and monitoring. The roadmap for this program includes obtaining and using new knowledge to improve existing forecasts, developing new suites of forecasts, and anticipating and mitigating the impacts of natural and human-induced hazards through use of new and more reliable information. The roadmap also envisions fully leveraging multi-agency, multi-sector commitments and expertise to accelerate the transition of research into operations for beneficial use by decision-makers and the public (NRC, 2000, 2003).



Dollar amounts shown are approximate damages/costs in $ billions.

Location shown is the general area for the regional event. Several hurricanes made multiple landfalls.

Additional information for these events is available at NCDC WWW site
www.ncdc.noaa.gov/ol/reports/billionz.html

The U.S. has sustained 67 weather related disasters over the last 26 years with overall damages/costs exceeding $1.0 billion for each event. 55 of the disasters occured during or after 1990. Total costs for the 67 events were over $500 billion using an inflation/wealth index.

FIGURE 10.1 Economics demands continued forecasting improvements.

SATELLITE SYSTEM STATUS AND STRATEGY 2015-2025

The climate, hydrologic, oceanographic and other research communities benefit from the weather science and applications community (ref. NRC, CESDU, 2004). The latter community spans traditional weather forecasting (e.g., clouds and rain), chemical weather (e.g., air pollution), and space weather (e.g., solar-induced communications interference). Because the weather science and applications community depends on satellite weather observations as a primary source of regular data, all of these research communities share this dependence. The advances in scientific understanding and forecast capability during the four decades since the introduction of satellite meteorology have been remarkable, but further dramatic improvements will require gaining currently unavailable satellite weather observations during the next two decades. This section reviews current practices, weaknesses in the satellite system, priorities for improvements, and the implementation timeline.

BOX 10.1 Hurricane Prediction

Weather prediction has advanced greatly during the last few decades. Improvements in global observing systems, advances in data assimilation and numerical modeling, and higher efficiency and capacity of computing resources have all contributed to higher reliability and increased public confidence in weather forecasts. However, weather analysis and forecasting have not matured to the point where important gains are no longer achievable. Although the 2005 Atlantic hurricane season included some remarkably good forecasts (e.g., Katrina, three days before landfall near New Orleans), it also included examples of highly uncertain predictions that resulted in considerable social and economic distress for regions of the southern US coast. For example, Hurricane Rita was forecast to make landfall near the Galveston/Houston area, prompting major evacuations of those communities. The storm actually made landfall to the north of that region with little damage or impact in the two evacuated cities.

Hurricane Wilma (see figure) is another striking example of hurricane forecast uncertainty during the 2005 season. The major numerical models from October 21st agreed on Wilma's forecast track direction and on a landfall on the south Florida coast, but there were major differences in timing (along-track error). This type of uncertainty is not always solved by consensus or ensemble approaches, and leads to low forecaster confidence. In turn, the forecasts for Wilma's eventual impact on south Florida that were provided to the public and emergency managers in charge of evacuation were highly uncertain, and led to mass evacuations many days in advance of what was ultimately necessary, with great economic loss.

The primary cause for the numerical model forecast uncertainty was the timing of the interaction of an approaching mid-latitude trough with Wilma's steering flow. The amplitude and speed of the upper-level trough as it exited the southwest U.S. (radiosonde data-rich region) and entered the Gulf of Mexico (lacking in radiosondes) was uncertain. Special dropsondes released from the NOAA Gulfstream IV aircraft supplied limited observational sampling of the region, but in analysis-sensitive regions such as this one, *continuous* assimilation of data is necessary to significantly reduce initial analysis errors and improve the numerical model forecasts.

In this section, the Weather Panel provides recommendations for enhanced space-based observations, which could provide the types of observations needed to ameliorate analysis deficiencies and improve both numerical and human weather prediction.

Background

Weather is crucial to all societal and economic activities and has no geographical boundaries. Since the beginning of the space age, the operational and research weather satellites of NOAA, NASA, and DoD have well served the diverse weather community. The United States shares vast amounts of satellite data on a daily basis with international partners. Global exchange and exploitation of satellite data is a long-standing hallmark of the international weather community.

The panel's approach to advance weather science and applications from space draws on a proven foundation of increasingly capable global observing systems, modeling systems, and theoretical and computational advances. As satellite observations have progressed during the last 45 years, so also have data assimilation and numerical weather modeling capabilities, and theoretical understanding of weather processes. In the last 10 years the community has been building important new data assimilation tools to optimize use of global observing datasets. The U.S. - with leadership from NASA, NOAA, NRL and the Weather Science research community - is well-positioned to continue to fully exploit the opportunities of the future. However, organizational challenges remain.

Finding: NASA and NOAA are not well-organized to develop new science missions to continue advancing weather Earth science and applications from space.

Recommendation: Create a NASA/NOAA Earth Science Applications Pathfinder (ESAP) Program. The ESAP would allow all special missions or instrument flights to quickly take advantage of new capabilities to realize Earth Science Societal and Economic Applications—from research into operations.

The Current Satellite System and Near-Term Ramp into 2015-2025

The U.S. enjoys a successful and well-recognized Weather Satellite Program. NOAA and NASA have implemented both polar and geosynchronous operational satellite programs that serve a broad spectrum of users. NASA's completed Earth Observing System (EOS) provides new research results and important new capabilities that could be transitioned into NOAA operational programs. NASA's Earth System Science Pathfinder (ESSP) Program will provide some very important new space observations. The DOD also operates weather satellites and shares the data with the larger weather community.

Approved continuations and upgrades of the current satellite system are key factors to prepare for the decade of our ESAS recommendations, 2015-2025. In making its recommendations, the panel assumes that the NOAA/NASA GOES-R and NOAA/DOD/NASA NPOESS programs (http://ipo.noaa.gov/) will go forward with the current planned instrument complement (including CMIS on NPOESS, though recognizing the deletion of the Hyperspectral Environmental Suite (HES) for at least the early flights of the GOES-R, -S, -T, and -U series). The deletion of the hyperspectral IR sounder portion of HES is addressed below. The Panel assumes continued success of NASA's Aura (launched July 2004 with six years planned life) CloudSat (with 2 years planned life) and CALIPSO (launched April, 2006 with 3 year planned life). The panel also assumes that the Taiwan-US COSMIC Mission (launched April, 2006; Cheng et al., 2006) will continue.

During the next three decades, results from these key missions and the Block 2 NPOESS follow-on will play a central role in key ESAS focus areas, including observations of weather, climate, atmospheric composition, water, human health and security, and oceanography. The analysis and application of results from these missions (both recently-launched missions and missions due for launch in the period 2007-2014) will provide a strong foundation for guidance for the implementation of the priority missions identified by this study for the period 2015-2025.

During the development of recommendations for future missions, the panel noted that planned follow-on missions are at serious risk. For example, to reduce costs NPOESS was recently restructured, with many capabilities reduced or eliminated. Space weather capabilities from DMSP F16 and beyond were cut, and climate measurements were eliminated. Also, despite strong support for the Global Precipitation Measurement (GPM) mission in the ESAS Interim Report (NRC, 2005), NASA has announced another delay in this key Weather and Climate Mission. The Interim Report specifically recommended that the GPM mission be launched without delay. This mission is an international effort to provide more accurate and frequent precipitation measurements. With growing demand for water and with the impact of drought on society, the need to better understand the water cycle and the availability of water are of critical concern to all nations. GPM would build on the success of the Tropical Rainfall

Measuring Mission and would address a critical societal need. **The Panel thus reiterates in the strongest terms the recommendation that GPM be flown as quickly as possible.**

GOES-R does not include an operational coronagraph designated as a pre-planned product improvement for possible future GOES missions, and there is no operational follow-on to the critical L1 solar wind measurements being made by ACE. Moreover, GOES-R cut the Hyperspectral Environmental Suite (HES) and replace it with the GOES Sounder to be determined. Measurements from NASA's polar-orbiting Aqua satellite Atmospheric Infrared Sounder (AIRS) showed that better GEO vertical soundings than are currently available from the GOES are essential for improved weather forecasting (LeMarshall, 2005). Moreover, the sampling from polar-orbiting satellites is too small to observe and adequately predict the rapidly changing atmospheric conditions that lead to severe weather, including tornadoes, flash floods, and hurricanes (including both intensity and landfall prediction).

The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), or similar capability instruments with newer technology, can provide the needed soundings. Developed under NASA's New Millennium Program, GIFTS was designed to obtain 80,000 closely-spaced (horizontal ~4 kilometer), high-vertical-resolution (~1-2 kilometer) atmospheric temperature and water vapor profiles, every minute, from geostationary orbit.[1] Because of budgetary considerations, resulting partly from the Navy's withdrawal of support for a spacecraft and launch vehicle, NASA discontinued funding for GIFTS beyond FY 2005.

Therefore, the panel recommends that NASA complete the space qualification of a hyperspectral sounder and assure flight early in the 2010s, and that NOAA assure the ground processing system is ready for the demonstration. The committee further recommends the transition from demonstration to operational capability by 2018. The demonstration and transition to operational GEO hyperspectral soundings could be made within the NASA/NOAA Earth Science Applications Pathfinder (ESAP) Program, recommended in the "Background" section.

In the "Priority Tropospheric Weather Observations and Missions" section, the panel recommends flights of an all-weather GEO sounder and a GEO chemistry mission. Together, these three flights would form a robust and synergistic GEO "carousel" (similar to the Low Earth Orbit (LEO) "A-Train") bounded by the GOES-East and GOES-West satellites.

The vision and challenge of this panel is to combine the NPOESS and GOES missions with the NASA research missions and the international satellite missions to deliver the observations and products required by society. NPOESS requires about 30-40% (and GOES another 5-10%) of the annual U.S. expenditures of about $2.5B/year for Earth science and applications (ESAS) missions. The NPOESS program will be a working example of interagency and community interaction leading to the "transition of research to operational applications" for societal and economic benefit. A vision for the ESAS weather and related sciences without a central role for NPOESS and GOES would be very incomplete. NPOESS and GOES-R must maintain their requirements and objectives and carry their full complement of advanced technology instruments even if some are delayed. Otherwise, the ESAS weather data sets and recommended vital missions for 2015-2025 will be crippled.

The Baseline R&D and Observational Strategy for 2015-2025

In developing a baseline R&D and observational strategy for 2015-2025, the Weather Panel drew on many sources of information. In response to the ESAS RFI, the community provided more than 75 thoughtful weather–related responses. Further expert knowledge of the new challenges for weather science and applications was provided through agency roadmaps, and through published National Academy studies on research and technology planning. Agency scientists and leadership provided the panel considerable information in discussions and presentations. The Panel is also aware of needs and plans in the private sector.

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[1] See <cimss.ssec.wisc.edu/itwg/itsc/itsc13/proceedings/session7/7_1_lemarshall.pdf>.

New challenges are central to the development of a research and observational strategy for weather science for the decades ahead. Key physical, dynamical, and chemical processes associated with severe weather (e.g., hurricanes and tornadoes) are neither fully understood nor characterized, thus high priority is placed on measurements that will contribute to successful forecasting of such events. Key processes where further observations are need to advance understanding include the genesis and evolution of strong mid-latitude and tropical storms, major summertime precipitation systems, air pollution events, and global chemical weather characteristics. Research and operational forecast systems do not presently include all the processes or observations necessary to understand and predict the full range of weather systems. For example, the interactions between the chemical and physical properties of condensation nuclei aerosols and cloud water and ice, with the ensuing formation of a variety of precipitation patterns, are not adequately understood, modeled, or predicted. Improving air quality forecasts on regional to global scales will require furthering the understanding of the complex interactions among sources, sinks, transport, and chemistry of tropospheric gases and aerosols. Furthering this understanding will require significant advances in space-based observations. In the realm of space weather, many magneto-electro-dynamic processes are not well understood. Initiation of solar flares and coronal mass ejections, geomagnetic storm physics, and basic mechanisms of ionospheric irregularity formation and propagation are examples of areas that require significant measurement and research before forecasting requirements can be met.

As noted in the vision, shortfalls in knowledge about key weather events and processes place the US in a position where it cannot meet the nation's increasing requirements for improved predictions of major weather storms, events and processes. Moreover, the growing complexities of society and long-term population growth and movements have increased our vulnerability to damaging weather events. A considerable body of research provides clear directions for adapting to and mitigating high impact events through improvements to forecasts.

PRIORITY TROPOSPHERIC WEATHER OBSERVATIONS AND MISSIONS

In order to determine priorities for observations and missions, the panel considered inputs from the RFI process as well as from key presentations made by leaders in the community. The evaluation of the inputs was based on their potential to transform the science, promote societal applications, and advance forecasting, and their risk, readiness, and cost. The panel also considered the ability of the proposed measurements to address international or national plans and to address the goals of the Global Earth Observing System of Systems (GEOSS).[2] This process identified key applications and societal benefits, key science themes and questions, and key satellite observations listed in Table 10.1, leading to the conceptual missions proposed in Table 10.2.

The conceptual missions include tropospheric wind measurements; all-weather measurement of precipitation with high temporal resolution, sea-surface temperature (SST), temperature and water vapor, an operational radio occultation system for high-vertical-resolution, all-weather tropospheric temperature and water vapor profiles and stratospheric temperature profiles, aerosol and cloud property observations, an air pollution monitoring system with high time-resolution, comprehensive tropospheric aerosol characterization, comprehensive tropospheric ozone measurements, and a suite of space weather instruments consisting of a solar monitor, ionospheric mapper, and a system of 'space weather buoys' implemented through a constellation of magneto microsatellites. The GPS radio occultation measurements mentioned above are also useful for space weather and climate.

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[2] Sixty-one countries agreed on February 16, 2005 to work together over 10 years to develop an implementation plan for a coordinated, international, global system to observe the Earth on an ongoing basis. This global system, called GEOSS, will provide in-situ and remotely-sensed data and integration of those data to address diverse societal needs for Earth observations.

TABLE 10.1

Societal Benefit	⟷	Science Themes	⟷	Required Satellite Observations
• Enhanced forecasts for hurricane and cyclone tracks, severe winter weather, floods. • Public health-risk alerts associated with pollutant outbreaks and heat waves • Improved evacuation guidance for extreme weather-related hazards • Development of renewable energy sources/sites • Decision support tools for management of natural resources and civil infrastructure (water, wildfire abatement, communication systems) • New warnings of coastal environmental contamination and hazard conditions (influx of Portuguese Man of War)		• Ameliorate deficiencies in numerical model forecasts during severe weather events • Improved understanding of causes of high intensity and track evolution of hurricanes • Development of new suites of targeted use forecasts in air quality and space weather • Quantifying pollution emissions and determining aerosol characteristics that affect human health		• Direct 3-D winds over the oceans, the tropics, and the Southern Hemisphere where radiosonde observations are scarce. • Integrated SST and high resolution profiles of temperature, humidity, precipitation along coast and in all-weather conditions • Low-cost, operational profiles of temperature and moisture in lower stratosphere and mesosphere • Pollution variables across large continental regions (aerosols, tropospheric gases) coordinated with cloud and precipitation measurements

TABLE 10.2 Summary of Priority Missions*

Brief Description of Mission	Variables	Type of Sensor(s)	Coverage	Spatial Resolution	Frequency	Synergies with other panels	Related Planned or Integrated Missions (if any)
Tropospheric Weather							
Tropospheric Winds (3 options)	Vertical profile of horizontal winds	Wind lidar (preferred option)	Global	350 km horizontal; 1 km vertical	TBD	Climate Health Water	3-D Winds NPOESS
	Ocean surface vector winds	Scatterometer	Global	20 km	6-12 hr		
	Water-vapor tracked winds	Molniya Imager	N. Hemisphere	2km IR/WV imagery, 1km VIS imagery, ~25km vector spacing	15 min during 8 hr apogee dwell		
All-weather Temperature and Humidity Profiles	Temperature and humidity profiles in both clear and cloudy conditions; Surface precipitation rate; SST	Microwave array spectrometer; Precipitation radar	Regional or Global	25 km (humidity and precip. rate) and 50 km (temp) horizontal, 2 km (humidity and temp) vertical	15-30 minutes	Climate Health Water	PATH GPM
Radio Occultation	Temperature and water vapor profiles	GPS	Global	~200 m Vertical resolution	~ 2500 daily	Climate Health Water	GPSRO
Aerosol-Cloud Discovery	Physical and chemical properties of aerosols; Influence of aerosols on cloud formation, growth, and reflectance; Ice and water transitions in clouds	Multi-wavelength aerosol lidar, Doppler Radar, Spectral polarimeter, A-band radiometer, Submillimeter instrument, IR array	Global	200 m vertical	TBD	Climate Health	ACE

NOTE: Spatial Resolution & Frequency column entries are targets based on an assessment of expected future mission performance capability, and should not preclude more detailed study of mission trade space.

Space-based Measurements of Tropospheric Winds

Mission Summary – Topospheric Winds	
Variables	Vertical profile of horizontal winds
Sensor(s)	Wind lidar (preferred); Scatterometer, Molniya Imager
Orbit/Coverage	LEO, global
Panel Synergies	Climate, Health, Water

The panel began by identifying from the viewpoint of the weather science and applications community the current capabilities and projected requirements for observations of the vertical profile of horizontal winds. The correct specification and analysis of tropospheric winds is an important prerequisite for accurate numerical weather prediction (NWP). Despite recent advances in assimilation of radiances, improved accuracy and resolution of wind profile data remains an essential requirement for improved numerical weather prediction, because of the unique role it plays in specifying the initial potential vorticity, which is a key dynamic property that is a major determinant of atmospheric evolution. The value of accurate wind measurements in day-to-day weather forecasting is well-established. For example, the path and intensity of tropical cyclones are modulated by environmental wind fields (see Box 10.1). Reliable global observations of winds are also needed to improve scientific understanding of atmospheric dynamics, the transport of air pollution, and climate processes.

Both scientific and forecasting applications are severely limited by the lack of data on the vertical profile of the horizontal winds over the oceans, the tropics, and in the Southern Hemisphere, where radiosonde observations are scarce. Surface wind observations (from anemometers and scatterometers) and single-level upper-air wind observations (from aircraft and cloud-drift winds) can provide only partial wind information over data-sparse regions.

Satellite sounders provide good global coverage of microwave and infrared radiances, which can be assimilated directly for an accurate definition of temperature and humidity profiles. When this information is coupled with surface pressure information, the mid-latitude wind field can be estimated using the approximations of geostrophic and hydrostatic balance. In the tropics, however, the geostrophic approximation is less valid, and direct measurements of the wind are required to produce accurate analyses of the atmospheric flow. In the extra-tropics, wind data are important for identifying intense small-scale features, such as jet streaks, which involve strong departures from geostrophic balance. Because wind is ultimately related to the transport of all atmospheric constituents, its measurement is also crucial to improving our understanding of the sources and sinks of constituents such as atmospheric water, carbon, trace gases, and aerosols.

In summary, despite the recent advances and sophistication of modern data assimilation methods, large analysis uncertainties remain over wide areas of the globe, especially for the three-dimensional tropospheric wind field. More accurate and reliable, and longer-lead weather forecasts, driven by fundamentally improved wind observations from space, would have directly measurable societal and economic impacts. To identify and achieve an improved tropospheric wind-observing system by 2025, the Weather Panel recommends a phased approach that builds on the existing observing system, addresses major gaps, and prioritizes activities based on technical readiness and potential impact.

Phased Implementation of a Doppler Wind Lidar system (2015-2025)

The Panel recognizes that a Hybrid Doppler Wind Lidar (HDWL) in low Earth orbit (LEO) could dramatically improve weather forecasts (Baker et al., 1995; Atlas 2005), and that the HDWL is needed to make global measurements of the wind profile through the entire troposphere and into the lower stratosphere under a wide variety of aerosol loading conditions. In recognition of the importance of wind profile data, the ESAS Water Panel fully concurs with the Weather Panel's recommendation that the Lidar Horizontal Wind Profiling Mission should be a top priority.

Due to the complexity of the technology associated with a HDWL, the Panel strongly recommends an aggressive program to design, build, aircraft-test, and ultimately conduct space-based flight tests of a prototype HDWL. The Panel recommends a two-stage space implementation approach. The recommended two stages, discussed below, are critically dependent on an aggressive and on-going technology development program that supports both the coherent and non-coherent Doppler Wind Lidar (DWL) techniques, and all other technologies necessary for implementation of the HDWL operational demonstration mission.

Stage I: Because the ESA demonstration of a one-component wind lidar measurement with the non-coherent DWL technique does not address all the relevant techniques and technologies needed for the HDWL mission, the Panel recommends that NASA support the development and space demonstration of a prototype HDWL system capable of global wind measurements to meet demonstration requirements that are somewhat reduced from operational threshold requirements (NOAA/NASA Global Tropospheric Wind Sounder Workshop, 2001). A HDWL demonstration mission in the 2016 time frame should include the demonstration of a technique for both the coherent and non-coherent DWLs which would enable the global determination of two-dimensional (2-D) horizontal winds over the entire 0-20 km altitude range. All technologies critical to the operational demonstration mission, including all critical laser, receiver, detector, and control technologies, need to be demonstrated in this HDWL demonstration mission.

Stage II: Knowledge gained from the NASA HDWL demonstration mission, the ESA non-coherent DWL demonstration mission, and the ongoing NASA DWL technology program will be used to develop and launch a HDWL operational demonstration mission. This mission will demonstrate the full range of threshold wind measurement requirements for an operational HDWL system. The HDWL operational demonstration mission could be launched as early as 2022.

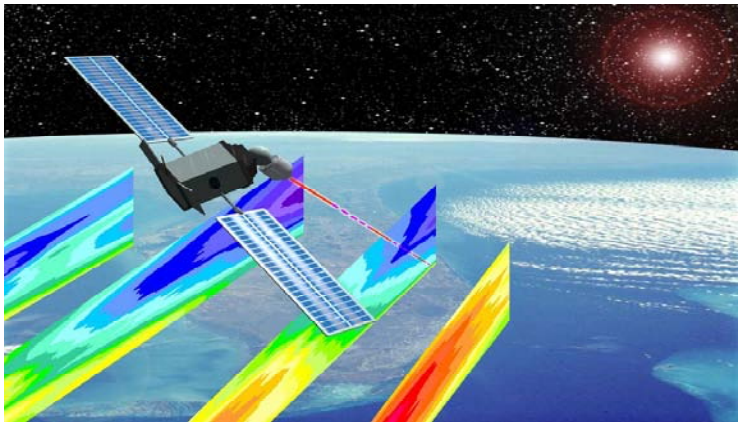
This mission will improve acquisition of global observations of wind profiles for assimilation into the latest numerical weather forecast models. There will be substantial societal benefits from this mission in the form of improved weather forecasts and severe storm predictions. There is also great potential for discovery in the seasonal and inter-annual measurements of winds, aerosols, and clouds from the tropics to the polar regions. Wind information will have direct benefits to security of human populations downwind of hazardous sources of gases or aerosols. It will also benefit the long-term atmospheric studies associated with climate change.

Other near-term opportunities for wind measurement from space

Scatterometer: In the near term, the Weather Panel strongly supports the continuation and improvement of over-ocean surface wind speed and direction observations using ocean scatterometer observations and the full ocean surface wind objectives for NPOESS.

Feature-Track Winds: More than 35 years of experience with the GOES satellites has demonstrated the value of high temporal and spatial resolution imagery for deriving feature-tracked winds. A major limitation of the satellites flying in the classical geostationary orbit is that they provide little useful coverage for regions beyond 60-65 degrees of latitude. The recently successful assimilation of experimental tropospheric winds over the polar regions that were derived from Terra/Aqua MODIS water vapor imagery (Velden et al. 2005) has led to a renewed push from both the operational and research communities for access to timely high-latitude water vapor imagery in the post-MODIS era. Unfortunately, the visible/infrared imager/radiometer suite (VIIRS; the operational MODIS follow-on) under development for NPOESS does not include a water-vapor channel because the NPOESS IORD-II does not specify a VIIRS polar wind measurement requirement. The panel recommends that this omission should be remedied in the fourth VIIRS sensor and beyond.

BOX 10.2 HYBRID DOPPLER WIND LIDAR



The HDWL is a combination of two separate Doppler Wind Lidar (DWL) systems operating in different wavelength ranges that have distinctly different, but complementary, measurement advantages and disadvantages. One DWL system would be based on a coherent DWL approach using a 2 μm laser transmitter and a coherent detection system. This type of system has been used extensively in ground-based Doppler lidars and more recently in a few airborne lidar systems. Because the operational wavelength of this system is in the near-infrared, the system has high sensitivity for making accurate wind measurements in the presence of aerosols, e.g., in the planetary boundary layer (PBL) or in aerosol-rich layers in the free troposphere resulting from, e.g., dust, biomass burning plumes, or clouds. By contrast, this type of system has low sensitivity for making wind measurements in regions with low aerosol loading which is frequently found in the free troposphere and above the tropopause.

The second DWL component of the hybrid DWL system is the non-coherent/direct DWL. This system operates at ultraviolet wavelengths and uses the non-coherent (or direct) detection of the molecular Doppler shifts to enable wind measurements in the "clean" air regions, but at a higher power cost. This technique has been demonstrated in a ground-based system, and an Instrument Incubator Program (IIP) project is underway to demonstrate it from an aircraft. The European Space Agency (ESA) has an aircraft demonstration of this technique in progress. ESA is developing the Atmospheric Dynamics Mission (ADM)-Aeolus to demonstrate the capability to globally measure one horizontal component of the wind vector using a non-coherent DWL technique from space (Stoffelen, et al. 2005). Aeolus may have the potential to make wind measurements from 0-20 km with vertical resolutions of 0.5 km (at 0-2 km altitudes), 1 km (2-16 km), and 2 km (16-20 km), with accuracies of 2 to 3 m/sec over this altitude range and a horizontal resolution or integration of 50 km.

Many developments are necessary to realize the full global 2-D horizontal wind measuring capability of a HDWL. The Panel recommends that all aspects of the HDWL be examined with respect to technical readiness and that an aggressive development program be implemented to address the high-risk components of the instrument package. This program should complement and leverage, where possible, the work being performed by ESA. In this section, the Panel provides its recommendation of a two-phase approach to developing and demonstrating an HDWL system to meet operational wind measurement requirements.

Molniya Orbit Imager: A promising solution to fill the time gap between MODIS and later NPOESS imagers (which may eventually include a water-vapor channel) is to obtain polar winds in a highly inclined eccentric Molniya orbit, which has been used by Russian communications satellites since the late 1960s. This orbit offers a promising vantage point for obtaining GOES-type imagery for the high-latitude regions. A satellite in this orbit, which has a 12 hour period, hovers nearly stationary over the high latitudes for about 8 hours. In addition to the winds product, a Molniya orbit imager has applications in numerous other areas, including monitoring/nowcasting of intense weather systems, sea ice tracking and model validation, snow cover and albedo monitoring, water quality, volcano monitoring/aviation safety, wildfire monitoring/ air quality, contrail/cirrus studies, cloud physics, Soil

Vegetation Atmosphere Transport (SVAT) model verification, and more. A Molniya Orbit Imager mission that includes a 6-channel visible/IR imager with GOES-R class horizontal resolution and image quality, and real-time data dissemination capabilities could be ready for launch in the 2010/2011 timeframe (Riishojgaard 2005). The imager for this mission would include at least two water vapor channels. This concept is the only known mission scenario that would provide high-resolution water vapor imagery and winds data for the high latitudes between the end of the MODIS missions in ~2009, and the launch of a suitably equipped NPOESS mission (which is unlikely before ~2019).

All-weather Measurement of Temperature and Humidity Profiles

Mission Summary – All-weather Temperature and Humidity Profiles	
Variables	Temperature and humidity profiles in both clear and cloudy conditions; Surface precipitation rate; SST
Sensor(s)	Microwave array spectrometer; Precipitation radar
Orbit/Coverage	MEO or GEO, global or regional
Panel Synergies	Climate, Health, Water

Here, the panel identifies from the viewpoint of weather science and applications the current capabilities and projected requirements for fine temporal resolution all-weather measurement (measurements in both clear and cloudy regions) of temperature and humidity profiles. Because microwave technology can also measure surface precipitation-rate and SST, and is the only technology that can provide all-weather capability, we consider the synergies of all four measurements.

Severe weather systems with intense rain or snow are always associated with dense and extensive cloud systems that are essentially opaque to the infrared and visible. Current operational microwave sounders have limited profiling capabilities in these weather systems. Yet, it is in these systems where the weather sciences and applications communities most need detailed ‘all-weather’ profiles of temperature and humidity, together with measurements of surface precipitation-rate. Over the mid-latitudes of the US and other mid-latitude regions, severe weather involving extensive flooding, snowfall or convective events with hail, tornadoes, and local flash floods always occur beneath a mass of largely opaque clouds. Likewise, the genesis and intensification of hurricanes always occurs beneath and within a mass of largely opaque clouds.

A capability for detailed ‘all-weather’ profiles of temperature and humidity, with surface precipitation-rate, would certainly improve forecasting the genesis, tracks, and intensity-changes of hurricanes, as well as the geographical distribution and magnitude of associated intense rainfall and storm-surges. The need for information about flood and storm-surge intensity during and after hurricane landfall is underscored by the unprecedented extent and intensity of the 2005 hurricane season in the U.S. If ‘all-weather’ profile observations from space, of the type just described, had been available during this devastating period, it is likely that more accurate and reliable long-lead forecasts would have reduced the loss of life and suffering.

Soundings of the three-dimensional atmospheric temperature and humidity profiles, under all-weather conditions, together with surface precipitation measurements, every 15 to 30 minutes, would enable significant improvements in forecasts. Besides improving the definition of the state of the atmosphere at the beginning of a forecast, the availability of such an observational data set would have an enormous impact on our understanding of weather processes and dynamics. The inadequacies of current numerical weather prediction models in representing the processes of cloud formation, evolution, and precipitation are widely recognized. Frequent all-weather observations of the kind described will provide vital new information on how to model crucial cloud and precipitation processes in the planetary boundary layer, through the depth of the troposphere, resulting in significantly more accurate numerical forecasts of severe weather.

Sea surface temperature (SST) strongly affects global transfer of moisture and sensible heat to the atmosphere. Hurricane genesis and intensification over the tropical oceans is very sensitive to SST. Recent results from the Tropical Rainfall Measuring Mission (TRMM) and other missions confirm that at moderate wind speeds, surface winds, and lower atmosphere humidity are responsive to SST perturbations. There is a clear need for cloud-independent SST measurements. Furthermore, understanding and forecasting El Niño and La Niña events requires the all-weather measurement of both SST and atmospheric conditions far beyond present capabilities.

Current capabilities and projected needs for All-weather observations

All-weather, space-based retrievals of profiles of air temperature and water vapor, together with surface precipitation-rate and SST, requires observations in the microwave region of the spectrum. Infrared observations are a viable alternative for temperature and humidity in clear skies, but infrared profiles are contaminated or blocked by clouds and cannot directly sense precipitation.

Imaging the complete Earth at a 15 to 30 minute refresh rate can, in principle, be achieved from a number of different Earth orbits. Current and planned future Low Earth Orbiting (LEO) assets, such as the AMSU, SSMI/S, and CMIS microwave spectrometers, are capable of retrieving temperature and humidity profiles and column-averaged precipitation on a global scale. They will provide the new, all-weather sea surface temperature information.

However, the temporal resolution from LEO cannot begin to approach 15-30 min without an impractically large constellation of platforms. Only Medium and Geosynchronous Earth Orbits (MEO and GEO) can reasonably deliver the required time resolution. Accommodation of an all-weather sensor suite on future GOES GEO platforms is one option. The GOES I-M Vis/IR imagers have demonstrated the value of sub-hourly image refresh rates for many applications. Adding a microwave spectrometer would expand GOES coverage to include cloudy cases, would permit the direct sensing of precipitation, and would generally enable the societal benefits noted above. MEO platforms are a second viable option. The lower orbit altitude would improve spatial resolution relative to GEO. But MEO remote sensing is a new approach with attendant technical uncertainty, thus its risks and benefits must be weighed accordingly.

Recommendation: Temperature and humidity profiles with surface rain-rate.

All-weather retrievals of air temperature and absolute humidity profiles require spectrometric observations of microwave emission along rotational transition lines of oxygen and water vapor. The lower energy transitions, in particular in the 50-70 and 118 GHz oxygen complex and the single 183 GHz line for water vapor, are best suited for penetration into clouds. These observations have not previously been obtained from a MEO or GEO platform, thus this effort would require significant new sensor development. Several competing engineering approaches are currently being developed to achieve this objective. They are deemed to be of sufficient technical maturity to warrant consideration as a new-start space mission in the 2010 time frame. Selection between the competing engineering approaches should be made using a peer review or competitive selection process.

Frequent measurements of precipitation profiles require an active microwave (radar) sensor. The LEO-based TRMM precipitation radar was the first such space-borne instrument. A MEO or GEO version of the TRMM radar would be needed to meet the 15-30 min temporal sampling requirement. The technology-readiness level of such a sensor is at present still too low. The panel encourages continued development of the technology necessary to mount precipitation radars on MEO or GEO platforms.

Therefore, the panel recommends, as a gap-filling alternative, the retrieval of surface rain rate (as opposed to precipitation profiles) using passive microwave observations, as demonstrated using SSMI (Ferraro, 1997), TRMM (Kummerow et al., 2001; Bauer et al., 2001) and AMSU (Gasiewski and Staelin, 1990; Bauer and Mugnai, 2003). This method requires the same microwave spectrometer observations as the temperature and humidity profiles, thus technology readiness is considerably more mature.

Operational Radio Occultation (RO) System

Mission Summary – Radio Occultation	
Variables	Temperature and water vapor profiles
Sensor(s)	GPS
Orbit	LEO
Panel Synergies	Climate, Health, Water

In an advanced data assimilation system, simultaneous availability of radio occultation (RO) measurements with microwave spectrometer profiles of temperature and water vapor from MEO or GEO would synergistically deliver substantially improved accuracy, precision, vertical resolution, and global coverage of temperature and water vapor. As discussed in this section, a constellation of small satellites providing RO soundings would complement the horizontally well-resolved microwave spectrometer soundings by adding independent, accurate and high-resolution vertical soundings in all weather on a global basis (including over the polar regions where soundings from MEO, but not from GEO, are possible).

A new, satellite, global observing approach known as radio occultation[3] (RO) - and sometimes termed GPS-MET – is a low-risk, inexpensive, high-payoff technology to obtain key information about temperature and moisture profiles in the lower stratosphere and the troposphere above the boundary layer, together with total electron content in the ionosphere.[4] This technology has the potential to further understanding of atmospheric thermodynamics and stratosphere-troposphere exchange, and ionospheric structure and behavior, and to make a major contribution toward improvement in regional and global weather forecasting, space weather forecasting, and climate benchmark observations. Thus, it provides excellent societal and economic benefits for a relatively low cost (~$10-20M /yr. when spread over a 5-6 year Mission).

Four successful RO space experiments have been flown.[5] The joint US –Taiwan Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC http://www.cosmic.ucar.edu/), which has orbited a 6-satellite constellation with both science and real-time forecasting applications, and an expected lifetime of 2006 – 2011, is the most recent and extensive of these experiments.

An operational RO system would comprise a small constellation of small-satellites carrying precision, space-qualified GPS receivers and supporting technology. The system would complement and add special capabilities (e.g., tropopause height detection) to the microwave and infrared temperature and moisture profilers on the U.S. operational polar orbiters (DMSP, NOAA, and NPOESS). The system

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[3] A history of radio occultation, the scientific and technical basis, and applications of the technique for weather, climate and space weather may be found in Lee *et al*., 2000.

[4] See Kursinski, E.R., G.A. Hajj, S. S. Leroy, and B. Herman, 2000: The GPS Radio Occultation Technique. *Terrestrial, Atmospheric and Oceanic Sciences (TAO*), 11, 53-114; Anthes, R.A., C. Rocken and Y.-H. Kuo, 2000: Applications of COSMIC to Meteorology and Climate. *Terrestrial, Atmospheric and Oceanic Sciences (TAO)*, 11, 115-156; Hajj, G., L.C. Lee, X. Pi, L.J. Romans, W.S. Schreiner, P.R. Straus, C. Wang, 2000: COSMIC GPS Ionospheric Sensing and Space Weather. *Terrestrial, Atmospheric and Oceanic Sciences (TAO)*, 11, 235-272; and Bengtsson, L, and Coauthors, 2003: The use of GPS measurements for water vapor determination. *Bull. Amer. Meteor. Soc*., 84, 1249-1258.

[5] The proof-of-concept experiment GPS-MET flew from 1995 to 1997. The German satellite CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) and the Argentine SAC-C were both launched in 2000 and are still operating successfully in early 2006. COSMIC was successfully launched on April 15, 2006 and is delivering high-quality soundings from six microsatellites (Cheng et al., 2006)

would also greatly enhance an independent, but closely related RO system planned by Europe on MetOp. A U.S. operational constellation of approximately six satellites would add more than 2,500 RO soundings per day to the GEOSS. When the European Galileo constellation is in place, the number of RO soundings obtained from a single LEO platform will approximately double, with no cost increase. Alternatively, with Galileo the number of spacecraft carrying GPS receivers could be reduced, with an associated cost decrease. COSMIC will provide data to help determine the optimal number of RO soundings per day over the globe.

Assuming that the five-year COSMIC mission will be completed as planned, the Panel recommends a follow-on operational, long-term RO system consisting of approximately six satellites that will meet the needs of both science and forecasting user groups. COSMIC should be supported by well-developed and tested ground analysis and data utilization tools. These will include advanced data assimilation methods to directly use the satellite measurements in both research and forecast weather models.

A Cross-disciplinary Aerosol – Cloud Discovery Mission

Mission Summary – Aerosol-Cloud Discovery	
Variables	Physical and chemical properties of aerosols; Influence of aerosols on cloud formation, growth, and reflectance; Ice and water transitions in clouds
Sensor(s)	Multi-wavelength aerosol lidar, Doppler Radar, Spectral polarimeter, A-band radiometer, Submillimeter instrument, IR array
Orbit	LEO, global
Panel Synergies	Climate, Health

Some mission concepts were regarded as having high priority by several ESAS panels, including the Weather Panel. This panel's top priority is a science mission to understand the linkages among clouds, aerosols and the Earth's hydrological cycle. This "Aerosol-Cloud Discovery" (A-CD) mission also addresses the high priority aerosol and cloud measurements needed for improved understanding of climate change and of hydrological processes.

As noted in the Overview, a key unknown is the complex and variable interaction of natural and anthropogenic aerosols with the Earth's clouds and precipitation events. The issue is important because aerosols serve as nuclei for cloud particles. Thus (1) the physical and chemical properties of aerosols affect the growth of cloud particles to precipitation size droplets; (2) the abundance or scarcity of aerosol can influence cloud reflectance; and (3) heating by dark aerosols can support cloud formation. Our knowledge of these interactions is poor. New measurements and knowledge of cloud-aerosol interactions is required in the 2015-2025 timeframe to improve the accuracy of hydrological forecasts of severe weather and reduce the uncertainties in climate change estimates.

An important further requirement of this mission is new knowledge regarding ice and water transitions in clouds, to be provided by new global measurements of the distribution of ice water path and weighted mean mass particle diameter. These global ice measurements should have the temporal and spatial sampling required for accurate regional-seasonal averages and assimilation into global systems to guide improvements of ice cloud representation and precipitation processes in global Earth System models.

Decisions regarding important environmental issues, such as global and regional weather and air pollution events, climate, and fresh water management will certainly benefit from both types of new knowledge.

The (A-CD) could be embarked on a free-flyer or be added to the instrument complement of approved missions which have not yet flown (e.g., GPM, NPOESS). The proposed A-CD instrument complement includes a multi-wavelength aerosol lidar for determining the vertical distribution of aerosol properties. This lidar could be a multi-wavelength High Spectral Resolution Lidar (HSRL), which has been shown to provide direct profile measurements of aerosol backscatter and extinction (Sroga et al., 1983; Grund et al., 1991) and aerosol microphysical parameters (Müller et al., 2002; Böckmann et al., 2005), or a multi-wavelength, multi-beam backscatter lidar, provided that this approach can be validated for determining the profile of aerosol properties, particularly in the vicinity of clouds. A multi-frequency Doppler radar is also needed on this mission for determining cloud content and vertical motions. The lidar and radar would complement passive measurements of the same cloud – aerosol fields from a spectral polarimeter and an A-band radiometer. Two additional instruments are required for the ice-phase measurements. The primary instrument measures at sub-millimeter wavelengths (frequencies between 183 and 874 GHz) to determine ice path; the second instrument is an IR array that observes ice water path, to improve retrievals of integrated water path retrievals while providing cloud height. The active-passive approach of this mission has a strong theoretical and practical application foundation.

Because the Panel has prioritized a global tropospheric aerosol mission in the chemical weather area, there would be strong cross-ties between the A-CD mission and other key ESAS areas. A-CD would strongly support improved weather forecasting of large and small precipitation events and address key climate science questions. The mission would also complement proposed Japanese and European missions and add to the understanding of international, long-term global records of aerosol, cloud properties, and precipitation.

REQUIREMENTS AND RECOMMENDATIONS FOR CHEMICAL WEATHER MEASUREMENTS

While "weather" is commonly understood to comprise tropospheric variations of temperature, wind, clouds and rain, chemical weather refers to the atmospheric variation of pollutants (e.g., aerosols and smog) affecting health, safety, commerce, and climate. Since the Industrial Revolution, chemical weather has become more complicated and important to understand, monitor, predict, and even control via local, regional, national, and even international policies and actions. Chemical weather can affect weather patterns, and perhaps less urgently but more importantly, can impact long-term (climatic) trends of severe weather.

The Weather Panel believes that the chemical weather missions recommended here are critical to the improvement of our understanding and ability to successfully monitor and predict chemical weather and its impact on tropospheric weather and climate. The Panel recognizes that NOAA and the EPA strategic plans have given high priority to the understanding and prediction of chemical weather, for both gases and aerosols. The Panel identified three high-payoff missions to produce important measurements to improve our understanding and forecasting of chemical weather, with both immediate and long-term societal benefits. These missions are:

- High Temporal Resolution Air Pollution Mission;
- Comprehensive Tropospheric Aerosol Characterization Mission;
- Comprehensive Tropospheric Ozone Mission

These three missions are independently important, but also highly synergistic, because they provide information at different temporal and spatial scales that together promise revolutionary improvement in knowledge and predictions of chemical weather. These missions will also have a significant impact on several other Decadal Survey themes. Earth Science and Societal Needs will be assisted by quantifying pollution emissions and assessing the quality of air we breathe, and by determining aerosol characteristics that directly affect human health. Human Health and Security will be addressed by improving air pollution forecasts for sensitive populations, thereby also improving air quality forecasts in general. Climate Variability and Change will be addressed by improved knowledge of ozone and carbon budgets, air pollution forcing of climate, and by relating aerosol and cloud characteristics to radiation budgets and precipitation.

TABLE 10.4 Summary of Priority Missions*

Brief Description of Mission	**Variables**	**Type of Sensor(s)**	**Coverage**	**Spatial Resolution**	**Frequency**	**Synergies with other panels**	**Related Planned or Integrated Missions (if any)**
Chemical Weather							
Air Pollution	Tropospheric column ozone, SO_2, NO_2, formaldehyde, aerosols; Vertically resolved CO	UV-VIS and SWIR-IR spectrometer imagers	Regional (FOV > 5,000 km)	5 km horizontal	< hourly	Climate Health	GEO-CAPE
Tropospheric Aerosol Characterization	Aerosol extinction profiles, real refractive index, SSA; Aerosol optical depth, size distribution, size-resolved real refractive index, non-spherical particle fraction in troposphere	Multi-wavelength lidar; Along-track and cross-track multi-angle passive polarimeter imager	Global	~150 m vertical; 20 km horizontal	3 days	Climate Health	ACE GACM GEO-CAPE Glory
Tropospheric Ozone	Tropospheric ozone; Ozone precursors; Pollutant and trace gases (CO, NO_2, CH_2O, SO_2); Aerosols ; CO with day/night and vertical sensitivity	UV-VIS spectrometer, SWIR/IR spectrometer, Future: Ozone/aerosol lidar	Global	Various: columns for ozone and ozone precursors in first phase with some vertical resolution for CO; <2 km vertical for ozone and 150 m for aerosols with lidar in second phase		Climate Health	GACM GEO-CAPE

NOTE: Spatial Resolution & Frequency column entries are targets based on an assessment of expected future mission performance capability, and should not preclude more detailed study of mission trade space.

BOX 10.2 SMOG

Major pollution episodes can result from a mixture of hydrocarbons and nitrogen oxides emitted from automobiles and industrial activities in many urban areas across the world. This is an example of a pollution event observed in Los Angeles, California, on August 10, 2003 (photo courtesy PDPhoto.org). Conditions like this are common for major metropolitan centers under slow moving summertime high pressure conditions; however, predicting the level of pollution associated with ozone and particulates is extremely difficult. The impact on the suburbs and regions down-wind of the urban centers is even more difficult to forecast. This problem is exacerbated by the lack of knowledge of the composition of the air up-wind of the city. Long-range transport of ozone precursor gases from other regions/continents can significantly change the initial conditions for pollution formation and make forecasting pollution even more difficult. Space-based measurements of ozone, ozone precursors, aerosols, and other pollutants with high-spatial and temporal coverage over North America, with more general coverage globally can revolutionize our ability to predict pollution episodes. These improved forecasts will provide the critical time needed to mitigate the affect of the pollution on human health and activities and other socioeconomic impacts on animals, plants, property, and businesses.

High Temporal Resolution Air Pollution Mission

Mission Summary – Air Pollution	
Variables	Tropospheric column ozone, SO_2, NO_2, formaldehyde, aerosols; CO with vertical sensitivity
Sensor(s)	UV-VIS and SWIR-IR spectrometer imagers
Orbit	GEO
Panel Synergies	Climate, Health

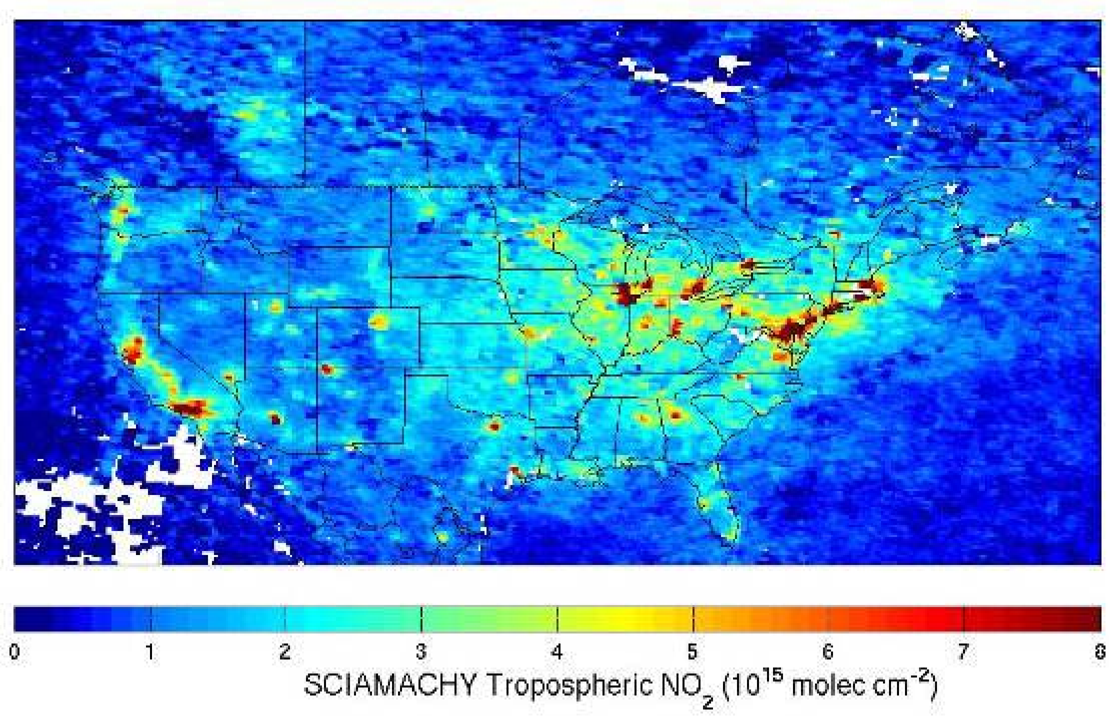
Because of the rapidly changing spatial distributions of primary and secondary pollutants in the planetary boundary layer (PBL) and free troposphere, a mission to continuously monitor air pollution in the lower troposphere across large continental regions would, for the first time, measure chemical weather on geographic scales necessary to develop effective policies to maintain good air quality. For this reason, the Weather Panel identified this mission as its highest priority chemical weather mission for the next decade (2010-2020). This mission was also identified by the Community Workshop on Air Quality Remote Sensing from Space (2006) as its highest priority air quality mission. The critical need for this mission has also been endorsed by the international atmospheric chemistry community in the Integrated Global Atmospheric Chemistry Observations Theme (IGACO) of the Integrated Global Observing Strategy (IGOS) (IGOS-IGACO, 2004).

The Weather Panel and the Air Quality Workshop concluded that the needed fine spatial and temporal resolution measurements to assess and predict regional to global air quality require a geostationary orbit (GEO), where the constraints on the measurements are significantly less than from the more distant Lagrangian (L-1) orbit. Moreover, some measurements could be made diurnally from GEO to examine regional transport and chemical transformations.

The measurements required of this GEO mission include tropospheric column ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), formaldehyde (CH_2O), and scattering and absorbing aerosols. Column measurements of O_3, SO_2, NO_2, CH_2O, and aerosols are needed during the day. The instrumentation must have the capability for high O_3 sensitivity down to the surface, including within the PBL. In addition, daytime total column measurements of carbon monoxide (CO) are needed, along with day and night measurements in the free troposphere. To capture the local to regional scale variations in these air quality parameters, measurements are needed at hourly or less frequency, at 5 km spatial resolution, with a minimum field of view of 5,000 km and a measurement accuracy comparable to similar instruments now in low Earth orbit (LEO), such as the Total Ozone Mapping Spectrometer (TOMS).

The combination of tropospheric column measurements of O_3, SO_2, NO_2, CH_2O, and aerosols, and the vertically resolved CO distributions will provide information on pollution sources and sinks, photochemistry, PBL dynamics, vertical transport in clouds, and horizontal transport. The CO measurements in the free troposphere across the same geographic region will provide the continuous connection between the more comprehensive daytime measurements of the other gases and aerosols. These data sets will be assimilated into numerical models (both numerical weather prediction models (NWPMs) and chemical transport models (CTMs) to improve chemical weather forecasting on urban to global scales. The Weather Research and Forecasting Regional Chemical Transport Model (WRF-CHEM) represents the type of model under development by NOAA to produce operational chemical weather forecasts.

Most of the needed instrumentation can be accommodated via adaptations of proven satellite instruments now operating in LEO, including the Ozone Monitoring Mission (OMI), SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY), and Measurements of Pollution in the Troposphere (MOPITT), thus offering relatively low technological risk. However, a few additional critical measurements are required on this mission to provide increased sensitivity of the column CO and O_3 measurements to concentrations of those gases in the planetary boundary layer (PBL). Provided that the technology can be developed in the next few years for these enhanced CO and O_3 column measurements from LEO, this mission could be ready for launch by about 2015.



BOX 10.3 AIR POLLUTION

Air pollution associated with O_3 is strongly affected by the amounts of photochemically-active nitrogen species (NO_x) that are present in the ambient air. Since the amount of NO_2 can be used as an estimate of the amount of NO_x and since most of the NO_2 is released by cars and trucks in the boundary layer near the surface, a measurement of the NO_2 column from space can be used to help forecast air pollution episodes. The above map of NO_2 column amounts across North America in August 2004 was created from SCIAMACHY measurements on Envisat. The major metropolitan regions in the Northeast and California are easily detected by their high levels of NO_2, as are the major cities in other regions across the U.S. Similar composite maps of O_3, CO, and aerosols can be created from space-based (LEO) instruments. Because air pollution is highly-variable in space and time, measurements of O_3, NO_2, CO, and aerosols are needed with high-spatial and temporal resolution, and this can be done most effectively from GEO orbit. These measurements will revolutionize air quality forecasting in a manner similar to how weather satellites revolutionized weather forecasting. In addition, since intercontinental transport of air pollution is a serious global issue, measurements of air pollutants and precursors with increased vertical resolution are needed globally to improve our ability to predict global air quality. Space missions to address these transformation measurement needs are discussed in this Chemical Weather section.

Comprehensive Tropospheric Aerosol Characterization Mission

Mission Summary – Tropospheric Aerosol Characterization	
Variables	Aerosol extinction profiles, real refractive index, SSA; Aerosol optical depth, size distribution, size-resolved real refractive index, non-spherical particle fraction in troposphere
Sensor(s)	Multi-wavelength lidar, Along-track multi-angle passive imager with cross-track swath
Orbit	LEO, global
Panel Synergies	Climate, Health

Aerosols are major contributors to local and regional air pollution, and they have important impacts on human health, atmospheric chemistry, radiation budgets, cloud formation, atmospheric dynamics, and precipitation amounts. Chemical weather objectives are dramatically affected by the composition, size distribution, and number density of aerosols in the troposphere, and the forecasting of aerosol properties and their impact can only be done with accurate and systematic global measurements. Numerical model initialization and validation requires finely resolved vertical distributions of aerosol properties. The Weather Panel determined that comprehensive characterization of aerosol properties could only be accomplished via a combination of polar LEO active and passive remote sensing measurements. This mission is complementary to the Weather Panel's Aerosol-Cloud Discovery mission and the high-priority Aerosol and Cloud mission advocated by the Climate Panel.

The measurements from this mission will be used to constrain and interpret the lower vertical resolution (but higher temporal resolution) aerosol measurements provided by the GEO Air Pollution Mission. The "calibration" of the GEO vertical aerosol measurements and the extension of this information to regions upwind and downwind of the GEO FOV, and globally, will provide additional critical data to significantly improve global chemical weather forecasting.

The aerosol properties to be measured include altitude profiles of extinction, real refractive index, and single scattering albedo with higher than 1 km vertical resolution and 20 km horizontal resolution, as well as backscatter and depolarization with better than 150 m vertical resolution and 20 km horizontal resolution. In addition, aerosol optical depth, size distribution, size-resolved real refractive index, and non-spherical particle fraction must be measured through the tropospheric column. These measurements must be made diurnally and globally along the ground track of a polar LEO mission. Accuracies should be consistent with the data assimilation and validation needs of numerical models, with special attention to the measurement of fine airborne particles with diameters less than 2.5 µm ($PM_{2.5}$) which are considered to be criteria pollutants for monitoring under the U.S. National Ambient Air Quality Standards (NAAQS).

A comprehensive characterization of aerosol properties requires the combination of simultaneous active and passive measurements which can only be practically done from LEO. The active measurements of aerosol microphysical properties can be provided by a multi-wavelength HSRL technique, or possibly by a multi-wavelength, multi-beam backscatter lidar technique, which is discussed in the section “A Cross-disciplinary Aerosol – Cloud Discovery Mission.” Passive column measurements of aerosol optical depths, single scatter albedo, size distribution, size-resolved real refractive index, and non-spherical particle fraction can be made using an along-track, multi-angle viewing technique with a significant cross-track swath width (e.g., 800 km) to enable nearly complete global coverage (>90%) in a less than 3 days. This would be a significant extension of the along-track passive aerosol measurements to be made by the Aerosol Polarimetry Sensor (APS), now under development for NASA’s A-train-bound Glory mission. The combination of the active and passive measurements will allow a more direct approach for altitude-dependent speciation of aerosol properties and the integration of these results into CTMs, allowing extension of the results between ground tracks and therefore providing truly global benefits.

The technology development associated with the HSRL is the primary pacing element for this mission. While there are some similarities with the technologies contained in the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), which was launched April 2006, the HSRL technique requires an advanced laser transmitter and receiver system. A proof-of-concept version has been flight tested, and a prototype of a high-power HSRL laser transmitter is being developed under the NASA IIP. This mission could be ready for launch as early as 2015.

Comprehensive Tropospheric Ozone Mission

Mission Summary – Tropospheric Ozone	
Variables	Tropospheric ozone; Ozone precursors; Pollutant and trace gases (CO, NO_2, CH_2O, SO_2); Aerosols; CO with day/night and vertical sensitivity; Tropospheric ozone and aerosol profiles with lidar in second phase
Sensor(s)	UV spectrometer, SWIR-IR spectrometer, Microwave limb sounder; Future: Ozone/aerosol lidar
Orbit	LEO, global
Panel Synergies	Climate, Health

Understanding and modeling tropospheric chemistry on regional to global scales requires a combination of measurements of O_3, O_3 precursors, and pollutant gases and aerosols with sufficient vertical resolution to detect the presence, transport, and chemical transformation of atmospheric layers from the surface to the lower stratosphere. Adequate vertical resolution is critical because of the strong vertical dependence in photochemistry and atmospheric dynamics that contribute to determining the budget of O_3 and other pollutants across the troposphere and lower stratosphere. The Weather Panel identified the Comprehensive Tropospheric Ozone Mission as high priority to provide the needed global vertical distribution of O_3, O_3 precursors, and other pollutants across the troposphere and into the lower stratosphere. This mission also strongly complements the Human Health and Security Panel recommendations to address air pollution and UV exposure issues.

The goal of the Comprehensive Tropospheric Ozone Mission is to make a significant improvement in our understanding of Chemical Weather processes on regional to global scales. To achieve this goal, this mission requires (i) the measurement of the global distribution of tropospheric O_3 with sufficient vertical resolution to understand tropospheric chemistry and dynamical processes in tropical, mid-latitude, and high-latitude regions, and (ii) the measurement of key trace gases (CO, NO_2, CH_2O, SO_2) and aerosols that are either related to photochemical production of O_3 or that can be used as tracers of tropospheric pollution and dynamics. This mission would use a combination of active and passive instruments to achieve the needed global measurements of tropospheric O_3, CO, and aerosol profiles and column measurements of O_3, NO_2, SO_2, CH_2O, and aerosols. The unique combination of measurements from this mission will provide data to validate numerical models under a wide range of atmospheric and pollution conditions from the tropics to the polar regions. These global measurements will directly complement the regionally-focused measurements from GEO and provide more detailed vertical information than can currently be provided from nadir-sounding passive instruments.

For this mission, the vertical resolution of O_3 measurements should be less than 2 km, with concurrent measurements of aerosols to less than 150 m. This can be accomplished using a differential absorption lidar (DIAL) system operating in the ultraviolet for O_3 and in the visible/infrared for aerosols. Measurements of CO, with contiguous coverage at the equator, are needed at 3-4 vertical levels in daytime and 2-3 levels at night, with a horizontal spatial resolution no larger than 5 km, including a surface reflectance measurement for PBL sensitivity. This capability exceeds what is available from current satellite instruments. Simultaneous column measurements of O_3, NO_2, SO_2, CH_2O, and aerosols are needed with a capability for increased sensitivity to O_3 near the surface. Except for the near-surface O_3 measurement, this capability could be implemented in a manner similar to current satellite instruments.

While the DIAL O_3 and aerosol profile measurements need to be made from LEO, the passive measurements of CO, O_3, NO_2, SO_2, CH_2O, and aerosols can be made globally with from either LEO or MEO, or even possibly L-1 with some compromise in performance. It is expected that in the next decade, it will not matter that the active and passive instruments will be on different platforms, because the data assimilation techniques will enable the seamless combination of data into an integrated numerical model.

Because the space-based O_3 DIAL requires significant technological development, the Weather Panel recommends a phased approach for the implementation of this mission. Because it is highly desirable that we complement the Chemical Weather GEO mission with a global tropospheric composition mission in the same time frame, the Weather Panel recommends that the passive portion of this mission be launched into a LEO orbit in the middle of coming decade (~2017) while all the components of the more complex O_3 DIAL mission are developed and tested by NASA for launch early in the following decade (2020+). In support of the DIAL O_3 development, NASA has begun initial funding of several key components as part of the Instrument Incubator Program (IIP). Since the active portion of this mission has high potential payoff for Chemical Weather, the associated technology development needs to be aggressively supported during the next decade.

The combined active and passive portions of this mission will provide new information on the chemistry and dynamics of the troposphere and lower stratosphere to guide the development and application of regional and global-scale CTMs. This will result in improved knowledge of chemical weather processes and better chemical weather forecasts. This mission is a natural follow-on to the current group of Aura and Envisat satellites that are making significant initial contributing to chemistry and air pollution investigations of the lower atmosphere. The addition of the new active and passive measurements of O_3, O_3 precursors, and pollutant gases and aerosols will greatly improve the understanding of tropospheric chemistry and dynamics, including the role of stratosphere-troposphere exchange in influencing the composition of the troposphere.

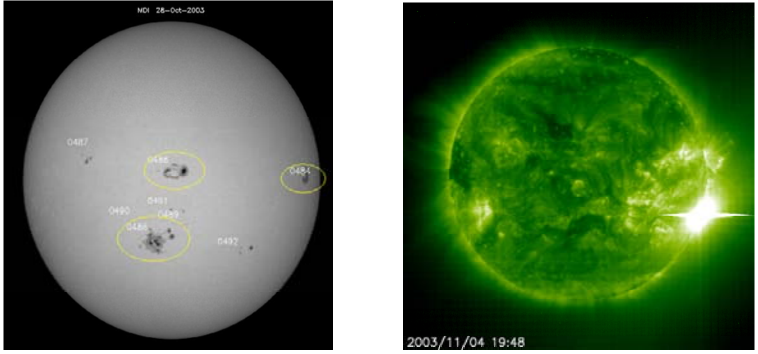
REQUIREMENTS AND RECOMMENDATIONS FOR SPACE WEATHER MEASUREMENTS

The basic goal of space weather monitoring missions is to forecast space weather conditions days in advance and to specify current conditions. The three highlighted missions in the Addendum address this need and are balanced in such as way as to provide comprehensive, multi-regional measurements that will not only improve forecast ability, but will help to answer many fundamental science questions related to space weather phenomena. To accomplish these goals, it is assumed that NOAA will continue to provide the essential data for operations and research from all current GOES space weather sensors, including: solar X-ray imaging, solar X-ray and EUV integrated whole disk measurements, as well as the *in situ* energetic particle and magnetic field measurements. It is also assumed that all planned DMSP satellites will launch, providing *in situ* and remote-sensed ionospheric data well into the next decade. Without the addition of pre-planned product improvements, NPOESS will provide no remotely-sensed space weather data, marking a huge reduction in capability over the next decade. The Panel expects the GOES-R program to add to space weather data, and suggests could more than presently planned. Other missions in planning are also expected to contribute proof-of-concept missions to operational Space Weather follow-on satellites; these include STEREO, Solar-B, Solar Dynamics Observatory, COSMIC, Radiation Belt Storm Probes, and C/NOFS.

The ESAS Weather Panel included Space Weather within its scope as charged. However, because much of its activity falls within the area of Sun-Earth Science (at NASA), and because the committee chose to focus its mission recommendations towards the Earth Science division within NASA, the recommended space weather missions from the weather panel are not included in the final synthesis mission list. The Weather Panel strongly believes that the space weather missions should be funded and we urge NASA to consider our recommendations in context with the solar and space physics decadal strategy (NRC, 2006).

BOX 10.4 SPACE WEATHER

During the last week of October 2003, the sun unleashed a massive assault on Earth. This assault took the form of electromagnetic energy, giant clouds of ionized gas called Coronal Mass Ejections (CMEs), and deadly high-intensity radiation. The subsequent sequence of events, now termed the ‘Halloween Storm,’ includes damage to, or destruction of, a vast array of technological systems.



Left: The solar active regions responsible for the Halloween Storm events (image credit – National Oceanic and Atmospheric Administration)
Right: The largest solar flare ever recorded, an X28, as seen in x-rays by the Solar and Heliospheric Observatory (SOHO) spacecraft. SOURCE: National Aeronautics and Space Administration).

Three sunspot groups were active on the sun by 27 Oct 03. Together, these groups produced a series of violent solar flares on the sun’s surface. From 22 Oct to 4 Nov, these regions produced 80 M-level (the second highest category) solar flares and 24 X-level (the highest category) solar flares, including three of the top ten most intense flares ever recorded, and an X28 solar flare on 4 Nov 03 that was the most intense ever. The energy from these flares disrupted worldwide radio communication systems and over-the-horizon radar operations.

The clouds of gas, CMEs, ejected in association with the flares, traveled at over a million miles per hour, arrived at Earth typically 2-5 days after each flare, and caused intense geomagnetic storms. In one case, traveling at an astonishing 5 million miles per hour, a CME reached Earth in only 19 hours. These severe storms produced further loss of communication systems, including military satellite communication, degraded GPS navigation, and induced commercial power problems in the United States and Northern Europe, in the most extreme instance causing a power outage in Sweden that affected 20,000 homes.

Perhaps the most devastating effect of these flares was the result of high-energy protons which can arrive in only 10s of minutes after a flare onset. The largest proton event, the fourth largest ever recorded, began on 28 Oct and lasted for three days. Hurtling towards Earth at near the speed of light, these subatomic bullets caused great havoc with the world’s satellite systems. Many satellite operators took protective measures to prevent problems, but even so 30 satellites experienced significant problems, including the permanent loss of a $650M Japanese satellite during one of the events. The radiation from these particles also posed a significant danger to aircraft operations, causing airlines to re-route flights to avoid the polar regions. The FAA issued it’s first-ever radiation alert for airline passengers above 25,000 feet. In addition, the astronauts on the International Space Station were moved into a radiation-protected area to prevent exposure.

In the end, that week went down in history as one of the most significant space weather events ever. The Halloween Storm is a reminder that, with little warning, severe space weather can disrupt systems all over Earth.

SPECIAL ISSUES, REQUIREMENTS, AND COMPLEMENTARY ACTIONS

The Panel strongly believes that a successful U.S. Weather Science and Applications from Space Program requires much more than new technology on satellites.

Fostering International Collaboration

More than 100 environmental satellites are launched each decade. Less than 20% are solely U.S. missions. Thus, it is important that some of our ESAS planning for weather continues to be done in coordination with international partners. We should use new and ever better ways to ensure free and open exchange of data and leveraging of complementary missions. Existing, substantial international collaborations on the TRMM, CloudSat, CALIPSO, GPM, COSMIC and other Missions demonstrate that U.S. ESAS has much to gain from more of these activities, including the emerging Global Environmental Observing System of Systems (GEOSS) as a new focal point for international activities, joining ICSU, COSPAR, and other proven mechanisms.

Complementary Non-Satellite Observing Systems

Great value is added to the weather ESAS by sub-orbital UAVs, ground- and ocean-based observing networks and *in situ* weather observations. In particular, the ESAS community recognizes the potential value of UAVs to complement satellite profiles of tropospheric and chemical weather variables. UAVs are particularly well suited for conducting tropospheric weather investigations in hazardous environments and when missions require long endurance, such as investigating and monitoring hurricanes. The ability to provide unique remote and *in situ* measurements that complement satellite observations can significantly improve forecasts of severe storms in data sparse regions (e.g., over the oceans). Likewise, the study of chemical and dynamical interrelationships in the troposphere and lower stratosphere require measurement capabilities over remote regions of the world, or at very high altitudes, where the unique capabilities of UAVs are particularly useful. It is only through detailed studies of complex Earth science processes using remote and *in situ* measurements from ground- and ocean-based and sub-orbital platforms that the satellite measurements can be properly interpreted. The synergism among different scales of measurements is essential for a complete and robust ESAS program.

The Essential Ground Segment: Models, Data Assimilation, and High-Performance Computers

The Panel recommends supporting cutting-edge models, data assimilation tools, and high-performance computers, which are critical for the success of the prioritized missions. A good portion of U.S. ESAS resources must be placed in a robust ground segment of NOAA, NASA, and partner agencies, with special access provided to the weather science research community. The priority observations and missions recommended by the Panel must be designed to optimize their incorporation into our modeling systems.

Full exploitation of the ESAS missions requires not only timely and substantive initial analyses, but also re-analyses as models and data assimilation systems advance. The productive use that the weather science community continues to make of re-analyses that are now somewhat obsolete is a testimony to their essential value. NOAA's relatively new Science Data Stewardship Program for satellite data records should be strengthened for use over the decades. The satellite records are a national asset and must be addressed accordingly. The advance of information technology and new methods for data assimilation will make re-analyses efficient, more accurate, and even more useful in extracting maximum information from the observing systems if the community appropriately plans for archiving of the required satellite data (NRC, 2005).

Transition of Science Results to Operations and to Users: Agency Collaborations

Without the required flow of new weather science research results to the users, the vision of the Weather Panel will not be realized. Societal and economic applications will be inefficient without the design of end-to-end, research-to-operations, and operation-to-users systems for the coming decades (see NRC 2000, NRC 2003a, NRC 2003b, and NRC 2004). These end-to-end data and product distribution systems are vital to a successful ESAS. Academia, the public, the private sector, and user groups must all be a part of the overall program of each new mission. Agencies leading ESAS need flexible mechanisms to work together and with external constituencies to fully exploit of ESAS in the coming decades.

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ADDENDUM
SPACE WEATHER OPPORTUNITIES AND PROPOSED RECOMMENDATIONS

Space weather information is needed most for the protection of technological systems that are vulnerable to space weather effects, and to ensure human health and safety. Radiation from solar flare particles and galactic cosmic rays presents a hazard for not only space-based systems and human spaceflight, and possibly for the crew and passengers of commercial and military aircraft. Airline pilots and crew members are among the most highly-exposed radiation workers in the nation, and they depend upon reliable space weather information to protect themselves and their passengers, as was done for the first time during the space storm of October 2003 (see Box 10-4). As the nation plans for manned missions to the moon and Mars, the ability for long-term prediction and warning of radiation hazards will be critical.

Some estimates place direct global economic impact of space weather at about $400M per year. Changes in flying routes due to high radiation and polar communication blackouts can cost airlines around $100K for each incident. A March 1989 geomagnetic storm caused $13M in damage to Quebec's commercial power grid. Total economic losses have been estimated in the billions. The economic impact of similar incidents in the Northeastern United States is potentially in the billions of dollars. Space weather events can also damage or destroy multi-million dollar satellite systems. During the October 2003 storm, one satellite was permanently disabled, and the operations of 30 others were disrupted.

Our national security interests can also be affected by space weather. The losses of satellite capabilities, relied-upon for everything from reliable communications to precision navigation, can impact our ability to perform military, disaster recovery, and humanitarian operations. Even loss of non-space-based communications systems (e.g., shortwave radio) due to space weather events has an impact our national capabilities. With our reliance upon space, or radio signals that pass though space, the idea of 'Space Situational Awareness' is becoming increasingly important. Knowing when and where our systems may not perform will be crucial to the future effectiveness of our nation's government.

SOLAR MONITOR

Our ability to specify and forecast changes in the solar atmosphere has societal and economic benefits that are of great importance. Astronaut health is protected when they take shelter or postpone a space walk to reduce their radiation exposure from a solar energetic particle event. The billion-dollar international space station arm is saved from harm when it is kept stowed during these same conditions. Because of their influence on radio communications at high latitudes, strong or severe radiation storms require airlines to divert flights from the polar regions. Large bursts of X-rays, which are often associated with radiation storms, affect radio communications on the dayside of Earth and degrade navigational capabilities. Ejections of large volumes of high-velocity coronal material result in the largest geomagnetic storms at Earth, requiring power companies to initiate changes in their operations to protect their equipment and customers. The effects of all these impacts would be lessened if only we better understood and could predict changes in the solar atmosphere at the sun, and how they evolve as they expand outward into the solar system. Predictive capability depends on answering many outstanding scientific questions. For example, when and where on the sun will solar active regions appear and when will they explosively erupt? What is happening on the far side of the sun and what will conditions be when far side features rotate into Earth view? Can we predict from solar observations, the solar wind conditions, especially its velocity, density and magnetic field, which will reach Earth several days after leaving the sun?

With the Solar Monitor mission, significant progress can be made towards answering these and other key solar scientific questions, and that will improve our ability to better serve society and those impacted by space weather. The Solar Monitor mission would consist of a full suite of sensors to completely characterize the solar surface, atmosphere, and heliosphere. An evolutionary approach would ensure that as technology evolves, more detailed and comprehensive measurements could be made. Elements comprising the Solar Monitor are:

Multi-spectral solar imagery. A broad spectral range of high-resolution solar imagery is necessary to characterize solar activity and features. White-light imagery allows the characterization of sunspots, a long-time measure of solar activity. This measurement is absolutely necessary, not only to support operational concerns for flare forecasting, but also for continuity and enhancement of a data record that dates back several centuries. Hydrogen-alpha imagery provides active region identification and analysis as well as solar flare monitoring. Ultraviolet and X-Ray imagery allow analysis of the sun's chromosphere and corona for active region development, magnetic field assessment, and coronal hole monitoring. Infrared imaging will allow direct measurement of coronal magnetic fields. A vector magnetograph will allow high-resolution determination of solar surface magnetic fields – a critical boundary condition for solar wind modeling and forecasting. Initial missions should be a combination of Earth-orbiting and L1, but over the next 10-20 years the missions should migrate closer to the sun, to both enable higher-resolution imagery of detailed solar processes and to increase warning time for solar wind disturbances. Multi-spectral imagers should eventually be placed in solar orbit (both equatorial and polar) at <50 solar radii, and plans should include highly elliptical coronal sampler probes. A current gap in our solar modeling and forecasting ability is lack of knowledge about conditions on the far side of the sun. Future missions should be placed to enable far side observations.

Coronal Mass Ejection (CME) Imaging. One of the most dramatic improvements to space weather forecasting would be the ability to three-dimensionally image and track Earth-directed CMEs. Operational STEREO-type platforms must be continued, as three-dimensional CME imaging will be essential to our ability to reliably predict geomagnetic disturbances.

In Situ Solar Wind. Measurements of the solar wind at L1 have greatly improved our ability to anticipate (in the short term) geomagnetic disturbances. L1 measurements are also vital for validating how well models based on solar observations predict conditions on Earth. Solar wind measurements along the sun-Earth line must continue and eventually be improved by making measurements closer to the sun (increasing forecast lead time) and by making multi-point measurements (to analyze CME structures). Eventual manned missions to Mars will require a solar wind monitor at the Mars L1 point.

IONOSPHERIC MAPPER

As our nation's dependence on GPS technology continues to grow, so does our need to specify and forecast conditions in the ionosphere that contribute significantly to GPS errors and outages. Surveying companies, deep sea drilling operations, land drilling mining, and military operations all struggle with the economic and societal impacts resulting from ionospheric effects on GPS. Military and commercial airline communications are affected by ionospheric conditions, especially in the polar regions, but also in their dependence on GPS at other locations. To alleviate these impediments to the use of modern technology, better space weather specification and prediction of conditions in the global ionosphere is needed. Yet, there are still many outstanding scientific questions that first need to be solved. The space weather research community doe not yet fully understand how the ionosphere varies in response to changing solar extreme ultra-violet (EUV) or how it responds to geomagnetic storms. The community does not yet understand the source of mid-latitude ionospheric irregularities or the physics of high/low latitude scintillation regions. These are only a few examples of scientific questions and space weather issues that can be addressed through improved satellite observations, such as those that can be made by the Ionospheric Mapper mission.

The Ionospheric Mapper mission is designed to improve the nation's ability to specify and forecast the ionosphere and it effects on High Frequency (HF 3 MHz – 30 MHz) through Super High

Frequency (SHF 3 GHz – 30 GHz) signal propagation. The primary measurements necessary are related to ionospheric plasma density and to variations in ionospheric signal amplitude or phase induced by small scale variations in ionospheric properties known as scintillation.

Geostationary UV Imager. A constellation of ionospheric UV imagers could drastically improve the ability to quantify ionospheric scintillation, a primary hazard for communications, radar, and navigation systems. As a phenomenon that is primarily confined to the equatorial and auroral regions, ionospheric scintillation is not ideally suited to measurements from low-Earth orbit Imaging the ionosphere from geostationary orbit has the potential to revolutionize how we characterize and predict ionospheric scintillation. Eventually, a pole-sitter type of orbit should be employed to provide continuous coverage of polar ionospheric conditions. UV imagers at the L1 and L2 points would provide unique local-time-stationary vantage points for ionospheric observing.

Low-Earth Orbit Ionospheric sensing. A low-Earth orbiting component is necessary to obtain *in situ* ionospheric plasma, electromagnetic field, and neutral atmosphere parameters. Remotely sensed data (e.g., UV imagery) can also be obtained at higher resolution to complement geostationary data. Data from low-Earth polar orbiters is the only way to characterize the high-latitude ionosphere and scintillation environment. Radio occultation instruments in this orbit would also provide a valuable data set for ionospheric modeling.

HIGH-DENSITY MAGNETOSPHERIC NETWORK

With hundreds of communication, navigation, military, and scientific satellites in low-Earth orbit through geosynchronous regions, there is a significant need to specify and forecast the space weather conditions in which these assets operate. Knowledge of space weather conditions is vital for the safe and successful operation of these spacecraft and to protect the enormous economic investment in the spacecraft and their instruments. Perhaps even more important, it is necessary to protect the societal services provided by these satellites. Satellite operators take actions to protect their systems based on forecasts of magnetospheric conditions, as they did during the Halloween Storms (see Box 10-4), but there are still many outstanding scientific questions that need to be answered to provide more timely and accurate forecasts of space weather conditions. The formation and depletion of particles in energy ranges from a few eV to MeVs must be understood to effectively protect national assets. While energetic particles, such as the so called MeV electrons are known to induce charging and damage in spacecraft components, the physical processes that energize these particles and the processes that cause the loss of these particles are not understood. There is much work needed to better understand the radiation belt environment surrounding Earth. We must obtain a better understanding of magnetospheric current systems (e.g., the ring current and field-aligned currents) that are so critical to geomagnetic storm evolution and intensity. A High-Density Magnetospheric Network will provide many of the observations needed to improve our understanding and to protect our resources and services.

The magnetosphere is a vastly data-starved region. A few point measurements are available operationally, but nowhere near the coverage needed to understand, detect, characterize, and predict the many multi-scale processes that occur throughout this tremendous volume of space. Yet, this is the medium within which nearly all of our satellites operate, and disturbances and changes in that medium can potentially have devastating effects on satellite systems.

Satellite-as-a-Sensor. Every satellite launched into Earth orbit can, and should, include a small on-board sensor to measure the *in situ* particle environment and include that information in any real-time data streams. Such sensors already exist, are quite small, and use very little power.

Microsat/Nanosat Networks. Even if every U.S. satellite contained an on-board sensor, coverage would still be insufficient to adequately characterize the magnetosphere. A huge step towards that goal would be a dense network of extremely small, low-cost microsats designed to sample the particle and electromagnetic field environment and to transmit results in real-time. Such a system, initially deployed throughout the inner magnetosphere, would allow for the possibility of advanced data assimilation and modeling systems for the magnetosphere, analogous to the current observational state for terrestrial weather. As technology improves, these sensors could exploit nanotechnology to produce smaller and smaller sensors that could be deployed in even greater numbers, eventually expanding into the outer magnetosphere and inner heliosphere.

RADIO OCCULTATION MISSION

An increased accuracy in space weather services allowing for a 1% gain in continuity and availability of GPS would be worth $180M per year. To achieve these economic gains it is necessary to improve our data assimilative ionospheric models, which will soon begin to utilize data from radio-occultation missions such as COSMIC. Of the space-based platforms potentially planned for the future, an operational COSMIC follow-on (e.g., COSMIC II) holds the most promise to work in synergy with the missions proposed here. Radio occultation measurements (vertical profiles of electron density and line-of sight total electron content) hold tremendous promise as an observational constraint on ionospheric modeling. Combined with ground-based measurements, they allow for accurate reconstruction of the entire three-dimensional structure of the ionosphere. The radio occultation instrument on MetOp could also contribute in this area, although it is not currently planned to produce ionospheric measurements.

Ground-based Systems: Several ground-based systems are also necessary to provide complementary measurements of the space environment. A global network of ionosonde measurements is absolutely necessary to provide bottom-side profiles of the ionosphere – the only means by which such information is available. Ground-based Total Electron Content measurements (using GPS receivers) provide a network of integrated line-of-sight measurements that are best utilized in combination with both ionosondes and space-based measurements. GPS and SATCOM receiver-based scintillation measurements provide the only *direct* measures necessary for global and regional scintillation specification and modeling. Incoherent Scatter Radars, currently only used for research purposes, could be exploited for operational use by providing plasma characteristics, electric fields, and ionospheric convection patterns (critical for accurate modeling). Ground-based magnetometers are necessary, primarily for geomagnetic disturbance specification and model initialization but also for continuity of long-term geomagnetic observations. Ground-based solar telescopes complement space-based platforms by providing solar observations at lower cost and greater flexibility, although the resolution and spectral coverage are insufficient to meet all requirements. Radio telescopes in particular are currently too large to place on space-based platforms and are thus most cost-effectively deployed on the Earth's surface.

11
Water Resources and the Global Hydrologic Cycle

> ". . . Water is becoming the scarce and precious commodity of highest value, not unlike the gold and silver that attracted settlers who came here more than a century ago. But a vital difference is that our water sources are a known quantity, and they are limited. At the same time, the stream of people relocating to western cities and town is seemingly endless . . ."
>
> *—Senator Larry Craig*
> *"Whiskey and water in the American West", editorial, January 13, 2006*
> *http://craig.senate.gov*

OVERVIEW OF GLOBAL WATER CYCLE RESEARCH AND APPLICATIONS

The global water cycle describes the circulation of water—a vital and dynamic substance—in its liquid, solid, and vapor phases as it moves through the atmosphere, the land, and the rivers, lakes, and oceans. Water affects everything—animal, vegetable, and mineral—on the surface of the Earth and in the oceans. Life in its many forms exists because of water and humans have flourished as a hydraulic civilization. Modern civilizations depend on mastering how to live within the constraints imposed by the availability of water—its excesses and its deficiencies (Figure 11.1).

Water is the link among most dynamic processes at the land surface. It controls the growth of plants both through water availability related to soil moisture and through radiation reaching the land surface—controlled largely by clouds—which is available for photosynthesis. Evaporation and transpiration from plants act to transfer not only water vapor, but also energy from the surface to the atmosphere, a feedback that has important implications for precipitation over the global land areas. The carbon, water, and energy cycles are strongly interdependent—latent heat flux is essentially proportional to evaporation, and photosynthesis is closely related to transpiration.

Snow cover, glaciers, and sea ice strongly affect climate through feedbacks between reflected solar energy and temperature. This feedback effect exists not only over the polar areas, but more seasonally and/or ephemerally over much of the Northern Hemisphere's land area, as well as high elevation areas of the Southern Hemisphere. Glaciers and ice sheets store much of the freshwater on the planet, but changes in this water storage occur at timescales of decades to centuries. However, the melting of ice sheets (mostly in Antarctica and Greenland) is a major contributor to sea level rise, and mid-and low latitude glaciers, while much smaller by comparison with polar ice storage, are important contributors to water supply over some parts of the globe. These glaciers are almost all in retreat, and will eventually lead to a loss of this source of usable water (see, e.g., Figure 11.2).

> "Does the United States have enough water? We do not know."
>
> *—National Science and Technology Council*
> *Subcommittee on Water Availability and Quality (2004)*

FIGURE 11.1 Water in many parts of the U.S., especially in the Southwest, is a critically scarce resource, demands on which have been exacerbated by population growth. SOURCE: Charles D.D. Howard.

FIGURE 11.2 Changes in the Qori Kalis Glacier, Quelccaya Ice Cap, Peru between 1978 and 2000. SOURCE: Courtesy of L. Thompson, Byrd Polar Research Center.

On a global scale, there are significant gaps in our knowledge of where water is stored, where it is going, and how fast it is moving. Global measurements from space open a vision for the advancement of water science, or hydrology. This vision includes advances in understanding, data, and information that will improve our ability to manage water and to provide the water-related infrastructure that is needed to provide for human needs and to protect and enhance the natural environment and associated biological systems.

The *scientific challenge* posed by the need to observe the global water cycle is to integrate *in situ* and space-borne observations to quantify the key water cycle state variables and fluxes. Our vision to address this challenge is a series of Earth observation missions that will measure the states, stocks, flows, and residence times of water on regional-to-global scales followed by a series of coordinated missions that will address the processes, on a global scale, that underlie variability and changes in water in all of its three phases.

The accompanying *societal challenge* is to foster the improved use of water data and information as the basis for enlightened management of water resources, to protect life and property from extremes in the water cycle—especially droughts and floods. The recent western U.S. drought (see Box 11.1) has renewed a focus on more effective management of water resources in the perennially water-stressed west. More generally, we believe that a major change in our thinking about water science that goes beyond its physics to include its role in ecosystems (Figure 11.3) and society is required as well. Better water cycle observations, especially at the continental and global scale, will be essential to this vision.

Water cycle predictions need to be readily available globally to reduce loss of life and property caused by water-related natural hazards, notably floods (see Box 11.2) and droughts. *We envision a future in which surface, sub-surface, and atmospheric water will be tracked continuously in time and space over the entire globe and at resolutions useful for timely inclusion into models for prediction and decision support related to use of water for agriculture, human health, energy generation, and hazard mitigation. Space-based observations and supporting infrastructure can help make this vision a reality for the next generation. Such predictions will have enormous social and economic value for the management of water, food security, energy production, navigation, and a range of other water uses.*

BOX 11.1
Drought in Western North America

Drought is a somewhat nebulous concept, for which there is no universal definition. All definitions, though, whether based on precipitation, soil moisture, or availability of water in rivers or reservoirs, are ultimately driven by conditions of abnormally low precipitation and/or high evaporative demand. These conditions are particularly chronic in areas such as the western U.S. where water is in short supply. The settlers of the 1800s found, for instance, that while land was in ample supply, the success of settlements was highly dependent on ample rainfall. Post-Civil War settlers flourished during a period when precipitation generally was ample, but immense hardship followed in the generally dry decade of the 1880s. In modern history, the Dust Bowl years of the 1930s made an indelible impression on a generation of Americans. Although the 1930s drought was not restricted to the West (see Figure 11.1.1), its implications were most serious there (recall that few of the major water systems now in place existed at that time). The drought of the 1950s was another widespread event, although its effects were felt more in the Great Plains region than in the far west. The most recent western U.S. drought began in the late 1990s, and persisted for at least 5 years over parts of the region. It has resulted in damages estimated in the tens of billions of dollars. Reservoirs in the Colorado River system in particular have declined to near record low levels (see Figure 11.1.2).

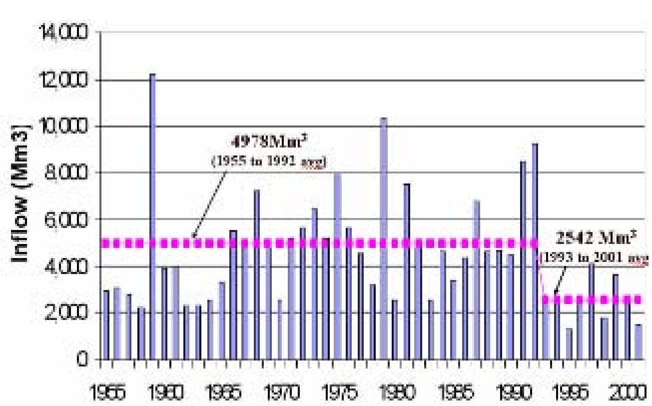

FIGURE 11.1.3 Rio Conchos discharge, 1955-2001. 1993-2001 discharge was less than half that of 1955-1992, and included the three lowest discharge years of record, yet precipitation over the same period was only about 10 percent below the long-term mean. Source: Vigerstol, 2002.

An important property of droughts in arid and semi-arid regions is that small decreases in precipitation can produce large decreases in runoff. Figure 11.1.3 shows streamflow in the Rio Conchos River of northern Mexico, a major tributary of the Rio Grande. The figure shows that during the 1990s, precipitation fell short of its long-term average by only about 10 percent. Runoff, however, fell dramatically, by about 50 percent. By contrast, for humid basins, a 10 percent drop-off in precipitation would produce only about the same decrease in runoff, which helps to understand why the severity and duration of droughts tend to be greater in the western U.S. than in the east.

Industrialized societies have generally become less susceptible to drought due to their ability to provide buffers to water supply, either in the form of reservoir storage or groundwater. Short, one or two year droughts in the Colorado River basin are barely noticed, for instance, because total reservoir storage exceeds four times the mean annual flow. On the other hand, the explosion of population in the “sunshine belt” of the Southwest is changing the balance of supply and demand, and the western states have been more aggressively pursuing management options, including drought plans. However, basic sources of hydrologic data that allow “nowcasting” and forecasting of drought evolution that are required for effective drought response are incomplete. Among the key deficiencies is information about the space-time distribution of soil moisture and snow water storage—information that is nearly impossible to obtain from *in situ* sensors, but which would be produced by the SMAP and SCLP mission concepts proposed in the section “Prioritized Observation Needs.”

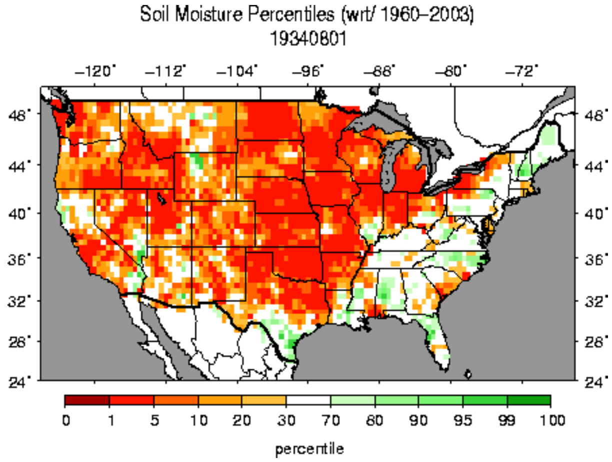

FIGURE 11.1.1 Drought extent in August, 1934. Soil moisture percentiles expressed relative to 1960-2003 climatology. SOURCE: www.hydro.washington.edu/forecast/monitor.shtml.

FIGURE 11.1.2 Lake Powell reached a record low level of 3555 feet MSL in April, 2005, over 105 feet below normal and corresponding to less than 50% of normal storage. By September 26, 2006 the water level had recovered to 3602 feet MSL.

BOX 11.2

Floods in Large Rivers—The Potential for Global Flood Forecasting

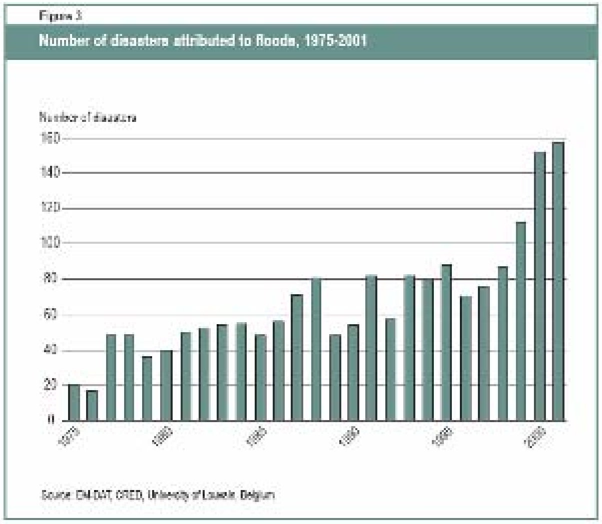

FIGURE 11.2.1 Number of major flood disasters globally, 1975-2001. SOURCE: UNDP, 2002.

Floods are among the most destructive of natural disasters. From a monetary standpoint, flood damages in the U.S. averaged around $5 billion per year in the 1990s, in 1995 dollars (Table 3.1, Pielke et al., 2002. Outside the U.S., the impact is even more striking; flood losses globally increased tenfold (inflation corrected) over the second half of the 20th century, to a total of around $300B in the decade of the 1990s (Kabat, P. and H. van Schaik, 2003). Aside from the economic costs, the social consequences of flooding can be staggering. The Mississippi River flood of 1927 displaced over 700,000 people and had impacts on the social structure of the lower Mississippi River valley that persist to this day (Barry, 1997).

Both the number of floods (Figure 11.2.1) and flood damages (in constant dollars) have been increasing in recent decades (UNDP, 2004). Although it is not clear whether climate change or increased levels of economic development is playing a greater role in these changes (Pielke, 2005), the trend is of great concern, both to governments and the insurance industry. Although the magnitude of flood losses is generally greatest in the developed world (losses from the 1993 Mississippi River flood were estimated to be about $15 billion, and for the Elbe River flood of 2003 about 9 billion Euros, or about $11 billion), the impact—both in terms of loss of life and economic—is greatest in the developing world. For instance, flooding associated with Hurricane Mitch caused an estimated US$3 billion to $4 billion in damages in Honduras which was almost 70 percent of that country's gross domestic product (GDP) (UNDP, 2002). By comparison, the 1993 Mississippi River flood damages represented less than 0.3 percent of the U.S. GDP.

Most of the developed world has reasonably sophisticated flood forecast systems. They are based on a combination of precipitation gauge and radar precipitation observations, river stage observations, and hydrologic models coupled with quantitative precipitation forecasts (QPF) derived from weather prediction models. However, these forecast systems are almost all regional in nature. For instance, in Europe, each country has an agency (generally affiliated with the weather services) that is responsible for flood forecasts in that country. In the U.S., flood forecast responsibilities lie with the National Weather Service River Forecast Centers, of which there are 13 (generally partitioned according to major river basins). On a global basis, though, there is no coherent flood forecasting capability as there is for global weather (Lettenmaier et al., 2006).

The absence of a global flood forecast capability impacts the developing world especially hard. In the Mozambique floods of 2000, for instance (Figure 11.2.2), there were only a handful of precipitation stations reporting on the Global Telecommunications System (GTS), and the precipitation radar systems that are a key element of flood forecast systems in the developed world were nonexistent. Yet, the capability for global flood forecasting clearly exists, particularly for large river floods which are responsible for most loss of life and economic damages (Webster et al., 2006).

FIGURE 11.2.2 The Mozambique flood of 2000 flooded over 19,000 square miles at its maximum, and damaged as much as 90 percent of the country's irrigation infrastructure. Some 45,000 people were rescued from rooftops. SOURCE: *Time* magazine.

Accurate flood forecasts require three things: good knowledge of the initial state of the land system—primarily soil moisture (and snow water storage, where relevant) and river levels, an accurate forecast of the space-time distribution of future precipitation, and an accurate hydrologic and river routing model. The missions proposed the section "Prioritized Observation Needs" will especially improve the ability to estimate initial conditions for flood forecasting: the proposed SMAP soil moisture mission will provide direct estimates of near-surface soil moisture, the SCLP cold lands mission will provide estimates of snow water storage, and the SWOT swath altimetry mission will provide estimates of initial conditions of river levels and flood plain storage. Other missions, such as atmospheric moisture profiles and transport will help as well to improve weather forecasts, especially in parts of the world where *in situ* (e.g., radiosonde) methods of measuring atmospheric profiles are sparse. Already, impressive advances have been made in the ability to "nowcast" precipitation in data sparse parts of the globe (Figure 11.2.3), and these nowcasts help as well (in combination with land surface models) to estimate soil moisture, following approaches pioneered in the North American Land Data Assimilation System (Mitchell et al., 2004). These advances, coupled with improved global water cycle observations, will not only facilitate the development of flood forecasts globally, but will enhance the quality of existing forecasts in the developed world.

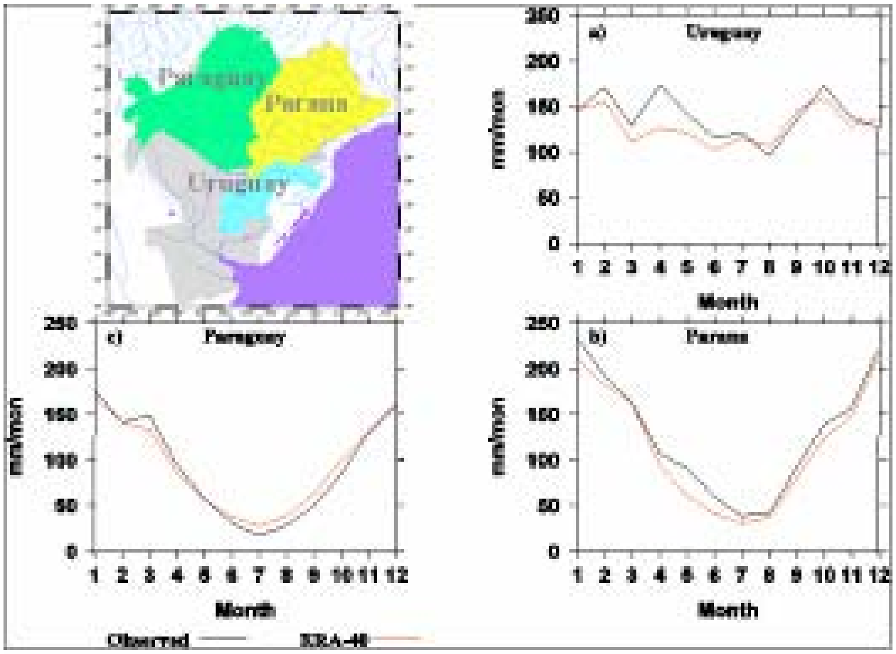

FIGURE 11.2.3 European Centre for Medium-Range Weather Forecasts' 40-yr global Re-Analysis (ERA-40) and observed (from gridded station data) mean monthly precipitation for the Uruguay, Parana, and Paraguay tributaries of La Plata River, 1979-99. The figure suggests that weather model precipitation analysis fields (for which ERA-40 is a surrogate) offer a viable alternative to surface networks to force land surface models, and in turn to estimate initial soil moisture for flood forecasts. SOURCE: Lettenmaier et al., 2006.

SCIENCE AND APPLICATIONS NEEDS AND REQUIREMENTS

The previous section offers a rationale for the importance of understanding the global water cycle as a major feature both of the Earth system and of human society. In this section, we present a strategic overview of planned and new water cycle missions and mission concepts that we believe should constitute the U.S. water cycle observing system from space over the decade 2010-2020. We also review the status and heritage of planned missions and program that are the underpinnings of the new mission concepts described the section "Prioritized Observation Needs." Our primary focus in this respect is on the Global Precipitation Measurement mission (GPM) and the National Polar-orbiting Operational Environmental Satellite System (NPOESS), for which we offer recommendations, forced by issues of immediate urgency to both programs.

Observing the Global Water Cycle: A Strategic View

Precipitation arguably is the most important part of the global water cycle. It dominates the land surface branch of the water cycle, and is second only to evaporation over the oceans. Furthermore, because the fraction of Earth covered by oceans is so large, even relatively small changes in the net of oceanic evaporation minus precipitation can lead to large changes in precipitation over adjacent land areas, so, indirectly, ocean precipitation strongly affects land conditions.

Over the last decade, the ability to observe the dynamics of tropical precipitation, and thereby better understand these dynamics, has advanced immensely. Much of this advance is attributable to the launch of the Tropical Rainfall Monitoring Mission (TRMM) in 1997, and the continuing data stream it has provided for over nine years. The improved understanding that has been gained by flying active and passive microwave sensors on the same platform has been instrumental in better characterizing precipitation not only from the TRMM sensors, but also from operational sensors such as the Special Sensor Microwave Imager (SSM/I). These improvements have come from a better understanding and interpretation of surface brightness (Tb) information at wavelengths that are most sensitive to precipitation. This improved understanding has also translated into better precipitation products from the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) sensor on Aqua, and forms the basis of the approved GPM.

The success of precipitation measurements from space forms a blueprint for strategic thinking about observation of "fast" storage terms in the global hydrologic cycle such as moisture storage in soil, in rivers, lakes, reservoirs and wetlands, and as ephemeral snow. While estimates of soil moisture are routinely produced from the AMSR-E sensor, their quality is at best experimental (the wavelength is too short to produce good soil moisture estimates for all but sparsely-vegetated areas), and the AMSR-E soil moisture product is insufficient to constrain the surface hydrologic models in any meaningful way. The same is true for snow water equivalent—especially in mountainous terrain which is critical to the water resources of many parts of the globe, such as the western U.S. Here the issue has to do primarily with spatial resolution. Aside from very large inland water bodies which are captured by ocean altimeters such as Ocean Topography Experiment (TOPEX)/Poseidon and Jason, surface water variations are not captured at all by current sensors. Estimation of river discharge from space remains an elusive goal.

Having high-quality estimates of these variables, coupled with measures of surface water storage and transport, would significantly improve the ability to model and understand the amounts and flows of surface water and in turn to provide an integrated understanding of the water cycle globally. The four highest ranked water cycle missions (listed in the order ranked) would contribute to this goal as follows:

- The approved *GPM* mission will provide estimates of precipitation at a sampling interval (3-4 hours) sufficient to resolve the diurnal cycle, and at a spatial resolution sufficient to resolve major spatial variations over the continents and oceans.
- A *soil moisture* mission would provide estimates of a key part of the land surface water balance, which controls land-atmosphere fluxes of heat and water over many parts of the globe (in

particular, recycling of moisture from the land to the atmosphere), and is a key variable that affects the nonlinear response of runoff to precipitation. Details are provided the section "Prioritized Observation Needs."

- A *surface water and ocean topography* mission (see the section "Prioritized Observation Needs") would provide observations of the amount and variability of water stored in lakes, reservoirs, wetlands, and river channels, and would support derived estimates of river discharge. It would also provide critical information necessary for water management, particularly in international rivers.
- A *cold season* mission (see the section "Prioritized Observation Needs") would estimate the water storage of snowpacks, especially in spatially heterogeneous mountainous regions that are the source areas for many of the world's most important rivers.

Taken together, these four missions would form the basis for a coordinated effort to observe most components of the surface water cycle globally. They also would provide critical information about precipitation over the world's oceans, and the basis for prediction of circulation in coastal areas that is not possible with current sensors.

In addition to measurements that would be made by these four missions, several other measurements that would benefit analyses of the water cycle were highly rated by the water cycle panel, with somewhat lower priority than the four identified above. These include missions that would estimate water vapor transport, sea ice and glacier mass balance, groundwater and ocean mass, and inland and coastal water quality (see Table 11.1). These measurements and water cycle issues are discussed in the section "Prioritized Observation Needs." All of these measurements have direct relevance to the needs of other panels as discussed in the section "Prioritized Observation Needs," and that synergy was considered in the selection of the integrated missions recommended in Chapter 3.

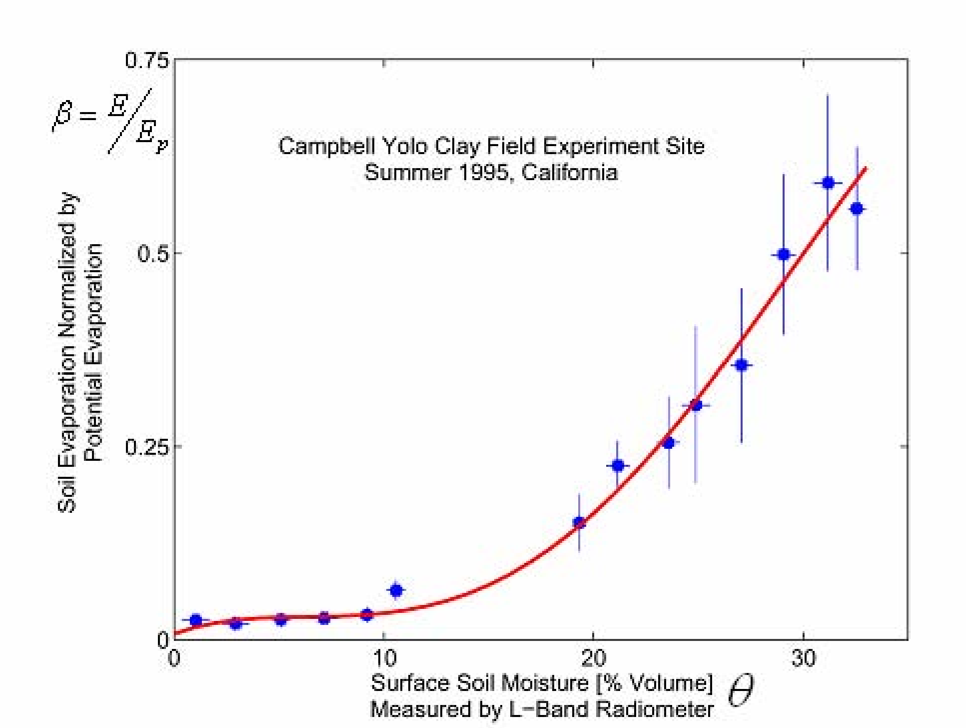

FIGURE 11.3 Soil moisture exerts significant control on evapotranspiration in terrestrial ecosystems. These field measurements of soil moisture using a truck-mounted L-band radiometer are plotted together with normalized evapotranspiration flux in a California agricultural field. As the soil becomes drier, the flux is reduced. Evapotranspiration is the key flux that links the water, energy and carbon cycles in terrestrial ecosystems.
SOURCE: Cahill et al. (1999).

Summary of Existing and Planned Missions and Products

As noted in Part 1, the queue of approved U.S. Earth science missions is remarkably sparse, especially those relevant to the global water cycle. It consists of CloudSat/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), which were launched April 2006; the GPM, which was further delayed 2-1/2 years by NASA in Spring 2006 despite this committee's recommendation against further delays (NRC, 2005). Aquarius, which will measure ocean salinity (and facilitate estimation of E-P (evaporation minus precipitation) over the oceans), is scheduled for launch in 2009. On the operational side, the staggering cost growth in NPOESS has resulted in cancellation or de-scoping of instruments that are central to water and climate science including cancellation of the Ocean Altimeter and cancellation/de-scoping of the Conical Scanning Microwave Imager/Sounder (CMIS). We do not discuss the implications of CloudSat/CALIPSO here in light of its recent launch; however, we do address the necessity and urgency for GPM, and for certain key water cycle variables that will be observed by NPOESS.

Global Precipitation Measurement Mission (GPM)

Precipitation is the central component of the global water cycle. It regulates the global energy balance through coupling to clouds and water vapor (the primary greenhouse gas) and shapes global winds and atmospheric transport through latent heat release. Precipitation is also the primary source of freshwater in a world that is facing an ever more severe freshwater crisis. Accurate and timely knowledge of global precipitation is essential for improving our ability to manage freshwater resources and for predicting high-impact weather events such as floods, droughts, and landslides.

The objective of GPM is to provide a reference standard for unifying a constellation of dedicated and operational microwave radiometers to provide accurate and frequent measurements of global precipitation for basic research and applications (Smith et al., 2006). The GPM core spacecraft will carry a first-ever, dual-frequency precipitation radar and a multi-frequency microwave radiometric imager with high-frequency capabilities to serve as a precipitation physics laboratory (with detailed microphysical measurements) and a calibration standard for constellation radiometers both in terms of brightness temperature measurements and precipitation retrievals. In addition, NASA will provide a constellation radiometer to be flown in an orbit that optimizes the sampling and coverage of global precipitation. GPM is thus the key to providing a uniform global precipitation data product leveraging off all available satellites capable of precipitation measurement. By extending the success of the Tropical Rainfall Measuring Mission (TRMM) to the entire globe with new capabilities to measure rain, snow, and precipitation microphysics, GPM is poised to improve the understanding of the water cycle, as well as the modeling and prediction of weather, climate, and hydrological systems.

GPM is currently in formulation at NASA and the Japan Aerospace Exploration Agency (JAXA), with potential participation of other international space agencies. As a complex international partnership, any further delay in launching the GPM Core spacecraft jeopardizes the mission by increasing the total cost and creating development problems for all partners. The viability of GPM will depend critically on NASA's commitment to a firm launch schedule thus providing a solid basis for securing international partnership. In reality, the President's FY07-08 budget supports a GPM launch in mid-2013 (rather than 2012 as suggested in NASA documents), which may further jeopardize the NASA-JAXA partnership. Maintaining the viability of the JAXA partnership adds another compelling reason for not delaying the GPM launch to 2013. As noted above, this committee has strongly recommended that GPM be launched without further delays (NRC, 2005), and repeats that recommendation here:

Recommendation: The committee recommends that GPM be launched in a timely manner, without further delay.

NPOESS

NPOESS was originally intended to include several measurements that are of key importance to climate and the global water cycle. These included a) snow covered area, which would be produced at high spatial resolution by the Visible/Infrared Imaging Radiometer Suite (VIIRS), similar to the Moderate Resolution Imaging Spectroradiometer (MODIS) product, and at lower resolution (but all-weather, or nearly so) by CMIS; b) snow water equivalent from CMIS (similar to AMSR-E); c) soil moisture from CMIS (6 GHz channel, assuming that AMSR-E radio interference problems at this frequency can be resolved, otherwise at 10 GHz), d) ocean surface height, from a nadir-pointing radar altimeter, and e) precipitation from CMIS. In addition, NPOESS was to include the capability to measure ocean wind speed and direction (needed for water vapor transport) and all-weather sea surface temperature (needed for evaporation estimation), both from CMIS. The CMIS instruments on all three NPOESS platforms were also intended to act as “constellation” satellites for GPM. The highest frequency (183 GHz) would facilitate retrievals of falling snow, not possible with AMSR-E or Defense Meteorological Satellite Program (DMSP) satellites. The recent cancellation of CMIS, and problems with VIIRS, call into question whether many of these observations will be made by NPOESS. The extent of the problem is difficult to determine until the nature of a downscaled CMIS replacement is known. However, it appears likely that the lowest frequency channel or channels will be lost. This would eliminate all soil moisture information that may have been available from CMIS. The viability of the snow product (which uses higher frequency channels that may survive) is not known. Similarly, the impacts on GPM are not known. While the proposed extension of the Special Sensor Microwave Imager/Sounder (SSMIS) will provide continued rainfall information, its resolution and thus quality of the retrieved rainfall products will be significantly degraded compared to CMIS.

Even in the absence of the CMIS difficulties, the NPOESS observations would have had significant limitations. The wavelengths (even with 6 and 10 GHz channels) are too short for soil moisture estimating other than in areas of sparse (or low biomass) vegetation. Hence, NPOESS would not obviate the need for a dedicated soil moisture mission. The nadir-pointing ocean altimeter would not have addressed the needs outlined in the section “Prioritized Observation Needs” of either the hydrology or oceanography communities for high resolution swath altimetry. In particular, it would not have provided the spatial resolution required for inland water and near-coastal applications, or the two-dimensional profiles needed for bathymetric estimation. For snow, the resolutions are quite coarse (around 15 km), and will not work well in areas with complex topography, or in forested areas. The cold lands mission proposal is specifically targeted at these issues. Nonetheless, the NPOESS data over selected low vegetation areas of modest topographic relief would be useful for validation of the cold land mission observations. For ocean surface wind, the wind direction measurements from CMIS would be poor at low wind speeds. Finally, the CMIS precipitation estimates will be much less useful without the “training” that will result from coincident observations from the planned GPM precipitation radar, which, as noted above, has been placed at risk by recent launch delays.

PRIORITIZED OBSERVATION NEEDS

The panel met for a total of 5 days to review and discuss the mission concepts submitted in response to the Request for Information submissions (RFIs). Of 47 RFI responses that were screened for possible relevance to the water cycle (Appendix 11.1) 20 were identified that were not of primary importance to other panels. These 20 RFIs were reviewed and sub-divided into two groups. The first group consisted of missions and instruments that are already slated to fly, or are presently in orbit. They included Aquarius, MODIS/Flora, and GPM. The proposal to measure evaporation was dropped because the panel is not confident that this can be accomplished with existing technology. Nevertheless, the panel recognized this as a key need, and the section “Next Generation Challenges” is devoted to issues associated with measurement and prediction of evaporation over the oceans and land. 12 mission concepts were aggregated from those that remained by combining RFIs that could be accomplished with data from the same sensors.

Table 11.1 summarizes the seven mission concepts identified by the panel in the order of their final ranking. Mission concepts were evaluated primarily from the perspectives of their potential contributions to science and to societal benefits. Secondary considerations were incremental mission cost, technological readiness, mitigation or backup for other missions, contribution to long term monitoring, consistency with multidisciplinary contribution to science or applications and technological readiness.

The panel conducted an iterative process of prioritization, using the criteria noted above. The panel found that the rankings were quite stable with respect to inclusion of secondary criteria (the ranking was ultimately based on an equal weighting of the two primary criteria, scientific and societal benefits). The panel also found that the first three mission concepts ranked substantially higher than the remaining four, and for this reason the first three are described in greater detail than the subsequent four. The panel also reaffirmed the critical importance of GPM. While GPM is an approved mission, the panel consensus was that if this were not the case GPM would be the highest water cycle priority, just as it was in the Easton post-2002 planning process (NRC, 2002).

TABLE 11.1 Candidate Missions in the Order Ranked

Brief Description of Mission	**Variables**	**Type of Sensor(s)**	**Coverage**	**Spatial Resolution**	**Frequency**	**Synergies with other panels**	**Related Planned or Integrated Missions (if any)**
Soil Moisture and Freeze/ Thaw State	Surface freeze/thaw state; Soil moisture	L-band radar, radiometer	Global	10 km (processed to 1-3 km)	2-3 day revisit	Climate Weather	SMAP Aquarius
Surface Water and Ocean Topography	River and lake elevation; Ocean circulation	Radar altimeter, Nadir SAR interferometer, microwave radiometer, GPS receiver	Global (to ~82° latitude)	Several cm (vertical)	3-6 days	Climate Ecosystems Health Weather	SWOT SMAP GPM NPP/ NPOESS
Snow and Cold Processes	Snow water equivalent; Snow depth; Snow wetness	SAR, Passive microwave radiometry	Global	100 m	3-15 days	Climate Ecosystems Weather	SCLP
Water Vapor Transport	Water vapor profile; Wind speed and direction	Microwave	Global	Vertical resolution		Weather Climate	3D-Winds PATH GACM GPSRO
Sea Ice Thickness, Glacier Surface Elevation, Glacier Velocity	Sea ice thickness; Glacier surface elevation; Glacier velocity	Lidar, InSAR	Global			Climate Solid Earth	DESDynI ICESat-II
Groundwater Storage, Ice Sheet Mass Balance, and Ocean Mass	Ground water storage; Glacier mass balance; Ocean mass distribution	Laser ranging		100 km		Climate Solid Earth	GRACE-II
Inland and Coastal Water Quality	Inland and coastal water quality; Land use/land cover change	Hyperspectral imager, Multispectral thermal sensor	Global or regional	45 m (global) 250-1500 km (regional)	~ days (global) Sub-hourly (regional)	Climate Ecosystems Health	GEO-CAPE

NOTE: The approved GPM mission, had it been ranked, would have been first.

Soil Moisture and Freeze/Thaw State

Mission Summary – Soil Moisture and Freeze/Thaw State	
Variables	Surface freeze/thaw state; Soil moisture
Sensor(s)	L-band radar, radiometer
Orbit	LEO, global
Panel Synergies	Climate,,Weather

Related RFI(s): Hydros (56), WOWS(27), MOSS(70)

Mission Objectives and Technical Summary

The soil moisture mission concept (termed SMAP, or Soil Moisture Active/Passive in Part I) is a pathfinder-class concept for global mapping of soil moisture and its freeze/thaw state with sampling and accuracies that meet key requirements for water, energy and carbon cycle sciences, weather, and climate applications, and natural hazards decision support systems. The technical approach is to make simultaneous active and passive low-frequency L-band microwave measurements. The radar makes overlapping measurements that can be processed to yield 1-3 km resolution. The radar and radiometer share a large deployable lightweight mesh reflector to make conical scans of the surface. This measurement approach allows passive microwave global mapping at 10 km resolution with 2-3 day revisit (Entekhabi et al., 2005). The SMAP concept draws heavily form the cancelled Hydrosphere State Mission (Hydros), but would include certain enhancements.

Several RFI responses included the Hydros/SMAP measurement approach at their core, but added more frequencies to meet broader requirements. For example the WOWS and Water Cycle Mission concepts would add additional and higher frequency microwave channels for snow, ocean winds, salinity, precipitation, and other variables. The MOSS concept would add a lower frequency (VHF) radar to allow deeper penetration sensing into the soil in order to characterize the root-zone soil moisture profile. The VHF radar would also be capable of sensing through more dense vegetation canopies. A key issue associated with VHF observations is the requirement for a very large (several tens of meters) antenna, technology for which is not yet developed. While the deep soil moisture measurements that the MOSS concept would support would be of great value to a range of science endeavors, the panel felt that the technology is a key constraint, and that the MOSS/VHF concept is better considered in the context of a broader long-term coordinated water cycle observation strategy (see the section “Next Generation Challenges”).

Science Value

Over land, soil moisture (and its freeze/thaw state) is the key variable that links the water, energy, and biogeochemical cycles (NRC; 1991). Soil moisture is a key determinant of evapotranspiration. The availability of soil moisture data will assist the water, energy, and biogeochemistry communities by allowing the linking of these cycles over land regions.

In boreal latitudes, the switching on and off of the land-atmosphere carbon exchange is coincident with the freeze/thaw transitions. Depending on the timing of the transitions, these areas can switch from a net source of carbon to a net sink. This transition, and its sensitivity to a warming climate, has been suggested as a possible component of the ‘missing sink’ in carbon cycle science (Myeni et al, 2001). A soil moisture mission will directly support science to reduce this major uncertainty.

Societal Benefits

Through its control on the rate of land-atmosphere exchange of water, soil moisture is a determinant of lower atmosphere water vapor and buoyancy flux. Experiments have demonstrated that the position and intensity of severe weather and the forecast skill of NWP models is extended when the model soil moisture state is realistically assigned (e.g., Chen et al., 2001).

Over land regions where seasonal climate prediction has most societal value, soil moisture is a major determinant of the climate state. The recycling of precipitation over continental regions is a significant feedback mechanism for persistent drought and flood events. Soil moisture is a key element of this feedback mechanism (e.g., Hong and Kalnay, 2000).

Additionally, it is a critical input into drought decision support systems. Rather than using proxy data for soil moisture as is currently the case in most drought monitoring systems (e.g., the Huang et al (1996) model used by the NOAA Climate Prediction Center), SMAP will provide realistic and reliable soil moisture observations that will potentially open a new era in drought monitoring and decision-support.

Floods depend upon both the amount of precipitation and the soil infiltration conditions (Box 11.2). The current practice of main-stem river flood forecasting and the delivery of flash-flood guidance to weather forecast offices are centrally dependent on the availability of soil moisture estimates and observations.

Complementarity

The soil moisture and freeze/thaw estimates from SMAP—as a measure of the state variable of terrestrial hydrosphere—will contribute to the disciplinary sciences across the Earth system community. Operational weather applications, climate science and seasonal climate forecasting, and terrestrial ecology and carbon cycle science all have links to soil moisture as the determinant of land-atmosphere exchange and as the state of the land branch of the water cycle.

The measurements would also allow all-weather high-resolution sea ice mapping and would provide knowledge of the soil background emissivity needed for snow water equivalent retrievals and solid Earth interferometry. Finally, for single looks SMAP retrievals of ocean salinity would not be as accurate as those of a dedicated salinity mission (e.g., Aquarius). However, through averaging in time (and reduction of effective spatial resolution) SMAP would be able to provide temporal averages of ocean salinity that would meet the Aquarius salinity accuracy standard of 0.2 PSU, and in turn would provide the basis for estimating climatological E-P over the oceans, which would be a useful constraint on two components of the global water balance..

Cost

The proposed SMAP soil moisture mission builds on significant system risk-reduction performed for the previous AO-3 ESSP Hydros mission. The understanding of the system components and costs are mature. The Hydros components and system are all at Technology Readiness Level 7 and higher. End-to-end cost of formulation, implementation, launch and operations is estimated to be approximately $300M (in 2006 dollars). The radar and radiometer share a lightweight mesh deployable antenna with significant cost-savings. This antenna subsystem has already undergone cost and engineering analyses including numerical and scale model testing.

Long-term Observations

Accurate and reliable soil moisture and surface freeze/thaw measurements will allow testing of complementary measurements (e.g., 6 and 10 GHz) from current and planned (e.g., GPM; NPOESS) sensors. The SMAP data set will provide much more accurate and higher-resolution information than can be retrieved from these higher frequency observations. The SMAP data will help to serve as a benchmark for determining where 6 and 10 GHz data (currently produced by TMI and AMSR-E, and (possibly) in the future by NPOESS) are usable, and their errors, so that at least partial global coverage (albeit not of the quality that SMAP will provide) will be possible past the end of the SMAP mission.

Multidisciplinarity

The global mapping of soil moisture has broad and significant multidisciplinary benefits to ecosystems, weather, climate, and applications aspects of Earth systems. Ecosystems are primarily limited by soil moisture and its freeze/thaw state. Weather and climate forecast models need mapped soil moisture observations as initial and boundary conditions. Many natural hazards applications are impacted by soil moisture status; examples include fresh water availability and supply, flood predictions, drought monitoring, and decision-support for malaria and other water-borne diseases.

Readiness

The SMAP concept is built on the foundations of low-risk and proven components. The concept requires a large (6 meter diameter) reflector in order to meet the resolution requirements. There are existing lightweight mesh reflectors with space heritage that are used for telecommunications. At L-band these reflectors have very low emissivity and are suitable for making Earth observations using both active and passive sensors. The SMAP components and system are all at Technology Readiness Level 7 and higher.

Surface Water and Ocean Topography

Mission Summary – Surface Water and Ocean Topography	
Variables	River and lake elevation; Ocean circulation
Sensor(s)	Radar altimeter, Nadir SAR interferometer, Microwave radiometer, GPS receiver
Orbit	LEO, global
Panel Synergies	Climate, Ecosystems, Health, Weather

Related RFI(s): WaTER (108), Hydrosphere Mapper (56) or OOLM (62)

Mission Objectives and Technical Summary

The Surface Water and Ocean Topography (SWOT) mission concept is a radar altimeter that would measure the height of inland water surfaces (rivers, lakes, reservoirs, and wetlands) and the ocean. Over inland waters, these measurements are critical to determining the location of and changes in stored water (in reservoirs, lakes, wetlands, and rivers) which are needed for the effective management of water resources globally, and of its movement (in rivers). Furthermore, knowledge of changes in seasonally and ephemerally inundated areas (e.g., flood plains) is important scientifically to the understanding of carbon exchange with the atmosphere, as well as the processes which affect flood plain evolution and biological processes in wetlands. Over the oceans and coastal areas, dynamic ocean surface topography controls ocean currents, and knowledge of spatial variations in static surface topography can be used to infer ocean bathymetry.

The SWOT concept will provide images (as opposed to tracks, as are observed by all current and past altimeters) of water surface topography at very high resolution (order of ten meters). When averaged over surface water areas of about 1 km^2, and linear distances of 10 km for slope (assuming a 100 m wide river channel), these images will provide surface topography measurements accurate to within several cm vertical precision and one microradian for slope, at repeat intervals of ~3 to ~21 days for latitudes up to 78^o. The coverage will be nearly global for all latitudes less than 78^o, and there will be only small gaps around the equator, which will not impact the spatial coverage of rivers, lakes, or mesoscale activity (Figure 11.4). For rivers, the mission would also be intended to recover channel cross-sectional profiles to within 1 meter vertical accuracy to low water, composited from multiple overpasses, which would provide a basis for estimation of the discharge of selected large (> ~100 m width) rivers via assimilation of surface elevation, slope, and channel cross-section into river hydrodynamic models. For the ocean, the mission would measure mesoscale topography with a height precision of several cm over areas less than 1 km^2, depending on latitude. It would extend the current sea level measurements into the coastal zones. A slope resolution of 1 microradian would also provide the basis for retrieval of global ocean bathymetry (small variations in gravitational attraction due to the contrast in density between sea water and the ocean crust are manifested in small slopes in ocean surface topography, which in turn allow retrieval of bathymetry when averaged over multiple overpasses so as to average out tidal effects).

The mission concept included here is similar to the Hydrosphere Mapper and WatER RFI responses, and is termed SWOT (Surface Water/Ocean Topography) in Chapter 3. The main difference between SWOT and Hydrosphere Mapper/WatER is the use of Ku, rather than Ka band for the swath altimeter (which results in improved performance during precipitation, with some reduction in vertical precision) and the use of a 21 day, rather than 16 day, repeat (10.5 and 8 day revisits, respectively) to avoid complications due to tidal aliasing for ocean retrievals. We retain in this section the original Hydrosphere Mapper configuration (Figure 11.5), but note the changes in SWOT as presented in Parts I & II. We also note that the decision between Ka (Hydrosphere Mapper/WatER) and Ku (SWOT) band is one that will require careful consideration, and should be the basis for a trade study.

To meet the science objectives, Hydrosphere Mapper would fly a suite of instruments on the same platform: a Ka-band near-nadir SAR interferometer (Figure 11.5); a 3-frequency microwave radiometer; a nadir looking Ku-band radar altimeter; and a GPS receiver. The Ka-band SAR interferometer is the same as has been proposed for inland water applications (WatER) and draws heavily from the heritage of the Wide Swath Ocean Altimeter (WSOA) and the Shuttle Radar Topography Mission (SRTM). The Ka-band synthetic aperture radar interferometer would provide centimeter precision with a swath of 120 km (including a nadir gap). The nadir gap would be filled with a Ku-band nadir altimeter, similar to the Jason-1 altimeter, with the capability of doing synthetic aperture processing to improve the along-track spatial resolution. Because the open ocean lacks fixed elevation points, additional sensors are required to attain the desired height precision: the microwave radiometer to estimate the tropospheric water vapor range delay and the GPS receiver for a precise orbit. A potential side benefit is that the GPS receiver could in principle also be used to provide radio occultation soundings (see the section “Prioritized Observation Needs”).

Orbit selection is a compromise between the need for high temporal sampling for surface water applications, near-global coverage, and the swath capabilities of the Ka-band interferometer. A swath instrument is key for surface water applications since a nadir instrument would miss most of even the largest global rivers and lakes. An additional issue is controlling the aliasing of ocean tides (or any other diurnal signal), for which the choice of a sun-synchronous orbit is problematic.

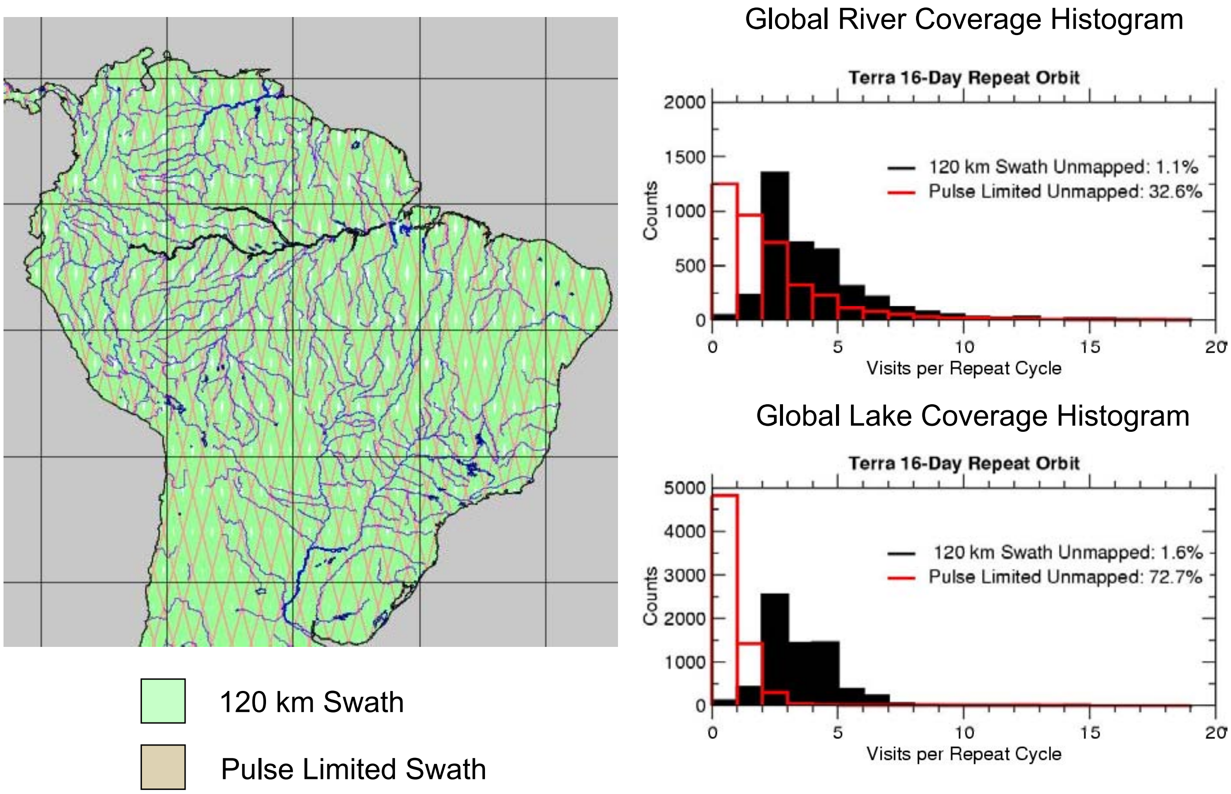

FIGURE 11.4 Spatial coverage of the proposed SWOT swath altimeter for a 16-day repeat mission. The swath of the instrument is shown in green, while the nadir altimeter coverage is in red. The figures to the right show the coverage of rivers and lakes for the swath instrument (black) and the nadir instrument (red). Even at the equator, near-global coverage is achieved by the swath instrument, whereas most global lakes and rivers are missed by the nadir instrument. SOURCE: Alsdorf et al. (2006).

To achieve the required precision over water, a few design changes to the SRTM design are required. The major one would be reduction of the maximum look angle to about 4.3^{o} which would reduce the outer swath error by about 14 times compared to SRTM. A key aspect of the data acquisition strategy is reduction of height noise by averaging neighboring image pixels, which requires an increase in the intrinsic range resolution of the instrument. A 200 MHz bandwidth system (0.75 m range resolution) would be used to achieve ground resolutions varying from about 10 m in the far swath to about 70 m in the near swath. A resolution of about 5 m (after onboard data reduction) in the along track direction can be achieved by means of synthetic aperture processing.

To achieve the required vertical and spatial resolution, SAR processing must be performed. Raw data would be stored on board (after passing it through an averaging filter), and downlinked to the ground. The data downlink requirements for all the ocean and land water bodies can be met with eight 300 Mbit/sec X-band stations.

Science Value

The change in water stored in lakes, reservoirs, wetlands, and stream channels, and the discharge of streams and rivers, are major terms in the water balance of global land areas. Yet both terms are poorly

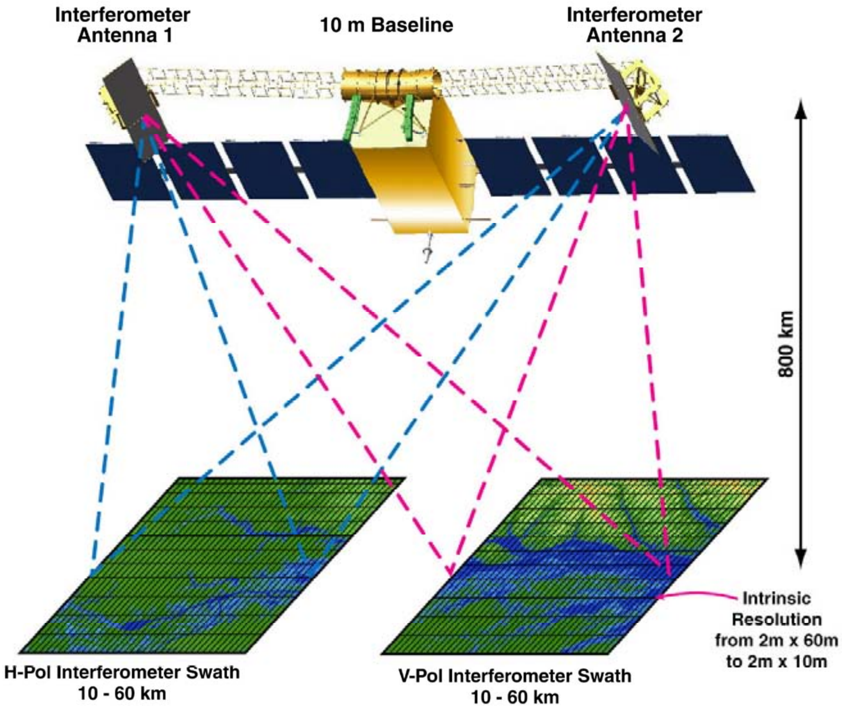

FIGURE 11.5 Conceptual drawing of the Ka-band Hydrosphere Mapper interferometer. Swaths on either side of nadir are mapped by horizontal (red) and vertical (blue) polarizations to avoid signal contamination. The spatial resolution will be 2m in the along-track direction and will vary between 70 m in the near-nadir to 10 m in the far swath. SOURCE: Courtesy of Ernesto Rodriguez, JPL.

observed globally; observations of these variables are now provided almost exclusively by *in situ* networks, the quality and spatial distribution of which varies greatly from country to country. More importantly, even where the density of *in situ* gages is relatively high, the point data are unable to capture the spatial dynamics of wetlands and flooding rivers (Alsdorf and Lettenmaier, 2003).

Over the open ocean, the scientific value of altimetric sea level observations has been well-established for ocean circulation, tides, waves, sea level change, ice sheet dynamics, geodesy, and marine geophysics. A large body of scientific publications has resulted from TOPEX/Poseidon and Jason-1 missions (see for example, Fu and Cazenave, 2001, and references therein). Nonetheless, despite the enormous contributions of nadir altimeters to the field, scientific understanding is limited, especially in coastal regions, by the coarse (300 km) resolution of these measurements. The swath altimeter would provide the basis for estimating coastal currents and ocean eddies, as well as global sea level.

In addition to the benefits for the land surface water cycle and oceanography, a swath altimetry mission would have important scientific benefits for weather and climate prediction, floodplain hydrodynamics, aquatic ecosystem and carbon dynamics, mesoscale currents and eddies, coastal processes, and ocean bathymetry. Furthermore, while the overpass frequency would not be sufficient for SWOT to fulfill a tsunami warning function, in cases where SWOT overpasses allowed it to capture tsunamis, these data could be extremely valuable for diagnosis of tsunami prediction models.

Societal Benefits

The paucity of global measurements of surface water storage changes and fluxes limits the ability to predict the availability of water in the future, and to predict flood hazards (IAHS, 2001). Furthermore, many major rivers cross international boundaries, but information about water storage, discharge, and diversions in one country that affect the availability of water in its downstream neighbors is often not freely available (e.g., Hossain and Katiyar, 2006). Major health issues such as malaria are also linked to fresh water storage and discharge. Yet, there is no source for either archival or real-time observations of these highly dynamic and sometimes ephemeral water bodies. While many benefits of the mission would be global in nature, there are important applications within the U.S. as well. For instance, a large investment is being made in restoration of the Florida Everglades, a large free flowing sheet of water that behaves like an unconfined river. Small variations in water surface elevations over this large area signal large changes in environmental quality, but are difficult or impossible to observe using *in situ* methods.

Notwithstanding issues that need to be resolved regarding how best to perform atmospheric corrections in near-coastal regions, a swath altimeter would provide greatly improved altimetry in coastal regions, where continued population pressures threaten resources. Currents and bathymetry from a swath altimeter would improve navigation and marine rescue operations, as well as planning for resource management. Marine operators currently use predictions of eddy currents to schedule oil drilling in the Gulf of Mexico and fishery managers use currents from satellites to pinpoint locations of target species. The swath altimeter would improve climate and weather forecasts. Hurricanes in the Gulf of Mexico have been shown to intensify over the warm Loop Current and its eddies (Goni and Trinanes, 2003), features not well resolved by the current nadir altimeters. Ocean circulation and climate models rely heavily on the assimilation of altimeter data for ocean circulation, but eddies and the energetic current systems are poorly-resolved and therefore do not accurately reflect the impacts of the smaller-scale processes.

Cost

For surface water applications, the swath altimeter would be sufficient, with total cost of roughly $300 M. For oceanographic and near-shore applications, the Ka-band nadir altimeter, and 3-frequency microwave radiometer would increase the cost by roughly $200 M, to about $500 M. These enhancements are included in the Hydrosphere Mapper (and SWOT in Parts I & II) mission concepts.

Long-term Observations

Long-term observations of river stage from the USGS will be invaluable for testing and evaluation of models and methods that will be needed to extend the surface altimetry observations, e.g., through data assimilation. Furthermore, the data for the stage of a relatively small set of global lakes that are large enough to be represented by TOPEX/Poseidon and Jason-1 will be extended. Similarly, long-term observations of sea level will be extended from the open ocean to the coastal regions.

Complementarity

The observations from a surface water mission would complement observations of global precipitation (from GPM), and soil moisture observations from the planned ESA SMOS mission and a proposed SMAP mission. They would also complement data from a proposed Cold Lands Processes Pathfinder mission, especially during the spring melt season when surface water dynamics change rapidly. The high spatial resolution sea level observations would complement ocean color measurements from MODIS, the Visible Infrared Imager/Radiometer Suite (VIIRS) aboard NPOESS, and a proposed hyperspectral mission to create a more complete picture of coastal ecosystems. The altimetric observations of eustatic sea level change, when compared to estimates of mass change measured via GRACE and GRACE-II would allow partitioning the sea level change between thermal expansion and increased ocean mass.

Multidisciplinarity

The surface water mission concept contributes to the ESAS climate variability and change, weather, human health & security, land use change/ecosystem dynamics/biodiversity, solid Earth hazards and dynamics, and societal benefits themes, in addition to water resources and the global hydrologic cycle. Among many possible examples, knowledge of changes in surface water over land can provide important information about long-term changes in climate (e.g., Smith et al., 2005). As noted above, knowledge of ocean surface topography helps to identify warm pools, which affect hurricane tracks and intensity. Water-borne diseases (malaria is a notable example) depend on surface saturation and/or ponding, which could be identified on a routine basis by swath altimetry (mapping is required; hence track altimeters cannot provide this kind of information). Changes in extent of wetlands, which would be visible as surface inundation by a swath altimeter, are important for ecosystem productivity. And, as noted above, making information about water stored in reservoirs freely available across international boundaries has many implications for societies, not the least of which is the potential to mitigate flood and drought losses.

Readiness

The surface water mission draws heavily from development work on the WSOA and the SRTM as well as the numerous radar altimeter and SAR missions. The technology is therefore relatively mature.

Snow and Cold Land Processes

Mission Summary – Snow and Cold Land Processes	
Variables	Snow water equivalent; Snow depth; Snow wetness
Sensor(s)	SAR, Passive microwave radiometry
Orbit	LEO, Global
Panel Synergies	Climate, Ecosystems, Weather

Related RFI(s): CLPP (19)

Mission Objectives and Technical Summary

Over most of the Northern Hemisphere land areas and the high elevation areas of the Southern Hemisphere, snow is a key component of the water cycle. In the western U.S., for instance, over 70 percent of annual streamflow originates as snowmelt, mostly from mountainous areas. The discharge of the major arctic rivers originates almost entirely as snowmelt. Yet our knowledge of this critical resource is extremely sketchy, and mostly comes from relatively sparse networks of *in situ* measurements, which at best can provide indices of snow water storage (for instance, the Natural Resource Conservation Service's SNOTEL network, which provides measurements of snow water storage over the western U.S., consists of about 600 stations). Measurements of the spatial distribution of snow water storage are essentially impossible to make using *in situ* methods, owing to extreme topography and/or remoteness of the areas where most snowfall occurs, and the expense associated with dense surface networks. On the other hand, both the temporal and spatial distribution of snow water storage is changing (see e.g., Mote et al., 2005), and better knowledge of these changes will be essential both for scientific purposes, and for water management.

The Snow and Cold Land Processes (SCLP) mission objective is to measure snow water equivalent (SWE), snow depth, and snow wetness over land and ice sheets at 100 m spatial resolution and 3-15 day temporal resolution. The proposed measurement approach will use dual mode high frequency

(X-, Ku- band) SAR and high frequency (K-, Ka-band) passive microwave radiometry in a multi-resolution configuration. Ku-band has demonstrated capability for estimating snow water equivalent in shallow snowpacks (Figure 11.6) and X-band provides greater penetration for deeper snow. The dual polarization (VV and VH) SAR enables discrimination of the radar backscatter into volume and surface components while the dual high frequency band selections would effectively sample a range of snow depths and improve the accuracy of retrievals. The passive microwave radiometer would provide additional information to aid the radar retrievals and would also provide a link to snow measurements from previous, recent and planned passive microwave sensors (SMMR, SSM/I, AMSR-E, and a proposed microwave imager on NPOESS C-2).

Two levels of measurement accuracy requirements for snow water equivalent will be addressed. In areas where shallower snow packs are predominant, differences of a few centimeters can have important hydrologic consequences. In deeper snow areas, such as mountainous areas where SWE often exceeds 100 cm, less stringent information is required. This leads to a two-tiered accuracy requirement of 2 cm RMSE for SWE less than or equal to 20 cm, and 10 percent RMSE for SWE greater than 20 cm. The minimum detection threshold is 3 cm. Observations are required over land areas above 30° latitude, and over ocean areas above 50° latitude, with specific exceptions for orbits over regions of interest at lower latitudes such as the Himalayas or the Sea of Okhotsk. As an exploratory pathfinder, global sampling is acceptable; complete observation coverage between orbital swaths is highly desirable but not required. Coverage beyond this domain is welcome and may benefit other observation needs and concepts, but is not strictly necessary.

To resolve important terrain-related processes, observations are required with spatial resolution on the order of 50-100 m to support the understanding necessary to link local-scale physical processes to the larger picture. This is the minimum baseline spatial resolution requirement. It is not essential, however, to have this resolution everywhere all of the time. A second mode of operation with a moderate sub-kilometer spatial resolution would often be sufficient as long as 50-100 m observations were regularly available to provide a link to higher-resolution local and hillslope-scale processes. The temporal drivers of the observing strategy are to resolve intra-seasonal and synoptic-scale snow accumulation and ablation processes. To resolve intra-seasonal changes in snow accumulation and ablation require temporal resolution of about 15 days. To resolve the effects of synoptic weather events, a shorter repeat interval of 3 to 6 days is needed.

Science Value

In the global water cycle, terrestrial snow is a dynamic fresh-water reservoir that stores precipitation and delays runoff. Snow properties influence surface water and energy fluxes and other processes important to weather and climate, biogeochemical fluxes, and ecosystem dynamics. The SCLP mission will fill a critical gap in the current global water cycle observing system. It will enable determination of the relevant spatial and temporal variations in the global distribution of cold-season precipitation, water storage, and surface fluxes. Snow covers up to 50 million km^2 of the global land area seasonally (about 34 percent of the total land area), affecting atmospheric circulation and climate from local to regional and global scales. The SCLP mission will provide initial and boundary conditions for numerical weather prediction models. It will also provide quantitative information needed to help understand the effects of snow on vegetation dynamics, soil moisture, soil freeze/thaw state, permafrost and biogeochemical fluxes.

Societal Benefits

One sixth of the world's population relies on water derived from seasonal snowpacks and glaciers (Barnett et al., 2005; see Figure 11.7). Fresh water derived from snow is often the principal source of

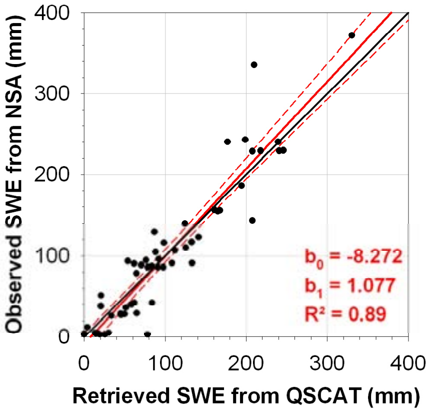

FIGURE 11.6 Comparison of SWE retrieved from QuikSCAT Ku-band data using a SWE radiative transfer model function with SWE analyzed from NWS National Snow Analyses (NSA) observations in and near the scatterometer footprints throughout a single season at four sites in the Colorado Rocky Mountains. SOURCE: Courtesy Don Cline, NOHRSC.

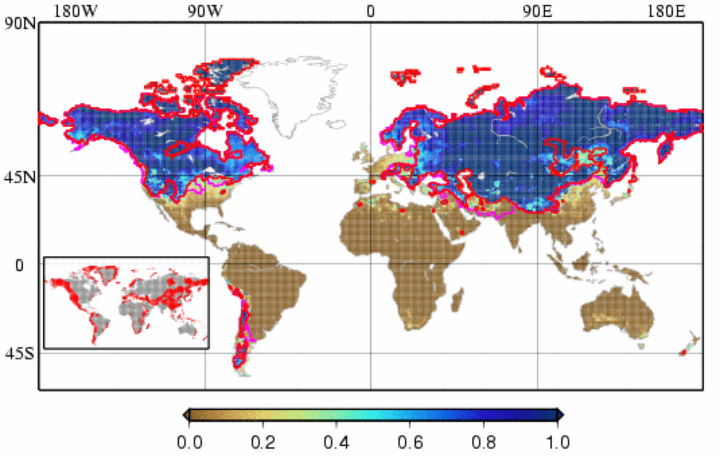

FIGURE 11.7 Accumulated annual snowfall divided by annual runoff over the global and land regions. The red lines indicate the regions where streamflow is snowmelt dominated, and where there is not adequate reservoir storage capacity to buffer shifts in the seasonal hydrograph. The pink lines indicate additional areas where water availability is predominantly influenced by snowmelt generated upstream (but runoff generated within these areas is not snowmelt dominated). The inset shows regions of the globe that have complex topography using the criterion of Adam et al. (2005).

fresh water for drinking, food production, energy production, transportation, and recreation, especially in mountain regions and the surrounding lowlands. This is not only true in high-latitude areas; snow is particularly important in many densely populated areas of North and South America, Europe, the Middle East, and Asia. Climate warming seriously threatens the abundance of this fresh-water resource, calling for immediate action to improve the understanding of climatic effects on water balance and hydrological processes. Snow can also be a significant hazard—snowmelt has been responsible for some of the most damaging floods in the United States. The SCLP mission will also help improve prediction of snowmelt-induced debris flows and periglacial dam breaches in mountain catchments.

Cost

Near the center of the options-cost envelope (approximately $300 M), the fundamental baseline mission concept is a dual-frequency, dual-polarization SAR combined with a dual-frequency radiometer at 19 and 37 GHz with H-polarization. Costs are reduced by using the same antenna for both the radar and radiometer, maintaining a simple deployment strategy for the antenna and solar panels, and by eliminating scanning mechanisms needed for wide-swath systems. If the budget were increased to the $500 M range, the instrumentation (dual high-frequency radar system and a radiometer) would remain essentially the same but would add global coverage with conical scanning (note that in the base configuration, there are gaps in coverage due to the relatively narrow swath, which conical scanning would expand).

Long -term Observations

The SCLP mission will extend measurements of snow covered area from optical instruments including the Advanced Very High Resolution Radiometer (AVHRR) and MODIS as well as passive microwave radiometers such as SMMR, SSM/I, and AMSR-E, by increasing the spatial resolution relative to previous passive sensors. Since the passive microwave measurements from SCLP are at the same frequencies as the past and present spaceborne radiometers, the SCLP measurements can contribute to a sustained record of over 25 years of passive microwave observations of snow properties. Furthermore, SCLP will enable establishing more accurate relationships with long-term *in situ* snow observations (e.g., snow pillows or manual snow courses), owing to its higher spatial resolution.

Complementarity

The SCLP observations would complement high- to moderate-resolution observations of snow cover extent from optical sensors like MODIS and VIIRS. Although the success of this mission does not depend on the existence on other missions, SCLP would complement past, current and planned low-resolution snow observations from passive microwave sensors (AMSR-E and, possibly, a proposed microwave imager on NPOESS C-2, depending on specifics of the CMIS replacement) and scatterometry (the European Remote Sensing [ERS] satellite, the SeaWinds Scatterometer on QuikSCAT, and the Advanced Scatterometer [ASCAT] on MetOp).

Multidisciplinarity

The SCLP mission concept will contribute to the climate variability and change, weather, land use change/ecosystem dynamics/biodiversity, weather, and societal benefits themes in a number of ways. For climate—changes in snow cover extent have key implications for the climate system, due to the strong contrast in albedo between snow covered and snow free areas. At shorter time scales, better knowledge of snow cover extent globally is an important land surface attribute for assimilation into weather prediction models. Ecosystem function in ephemerally snow covered areas depends strongly on snow cover status, and snowpack depth. Finally, as indicated above, snow water storage is a critical variable over much of the Northern Hemisphere land areas for water supply; hence the mission has important societal benefits.

Readiness

Because the proposed sensors have significant heritage, the technological readiness is high. The single shared pushbroom antenna will use low-cost, mature lightweight composite reflector technology flown on the SSM/I, QuikSCAT, and WindSat missions. The radar and radiometer electronic technologies also have a high level of heritage from current and past space missions. As noted above, SCLP in its base configuration is identified as a pathfinder class mission; however, a larger budget would expand the coverage to global which would support operational uses of the data. A formal technology assessment study is currently being performed for those instruments that are included in the ESA Explorer proposal—specifically the radar (the ESA proposal does not include a passive radiometer).

Other High Priority Water Cycle Observations

Water Vapor Transport

Mission Summary – Water Vapor Transport	
Variables	Water vapor profile; Wind speed and direction
Sensor(s)	Passive microwave; GPS
Orbit	LEO, Global
Panel Synergies	Weather, Climate

Related RFI(s): AIRS (8), GPS RO (92), WOWS (27)

Water vapor transport is a major component of the global hydrologic budget. The fresh water flux (E-P) must ultimately be constrained by the divergence of water vapor over oceans, and by the divergence of water vapor, surface storage (soil moisture, snow water equivalent), and runoff over land. Being able to simultaneously measure as many of these terms as possible thus constitutes a strong constraint on each of the elements of the global hydrologic budget and is of very high value to research effort aimed at understanding the flows and fluxes of the global water budget. The transport of water vapor can be broken into two distinct problems: The measurement of the vapor profile and the three-dimensional motions that transport the moisture. The measurement of vapor profiles can be accomplished through a number of combined infrared/microwave sounders such as the current AIRS/AMSU instrument aboard EOS Aqua or the CrIS/ATMS instrument being planned for NPOESS. Advances in radio occultation measurements expected from the COSMIC constellation (Sokolovskiy et al., 2006) show great promise in adding valuable water vapor information in the atmospheric boundary layer. Together, these measurements and expected progress from research will form the basis for estimation of global 3-dimensional water vapor fields. Still missing are the 3-D wind fields that transport this moisture. This is a high priority observation for the Weather panel (Chapter 10), but it is important to the global water cycle as well.

The transport of water vapor, coupled with the key hydrologic variables discussed in this section, all act to constrain the hydrologic variables and lend insight into their mutual relationships. For example, a recent estimate of the water balance in South America (Liu et al., 2006) was made by combining measurements from the sensors in Table 11.1—the sum of precipitation, water vapor transport, and river discharge was shown to be consistent with an estimate of a seasonal change in the continent's gravity (owing to changes in water storage). The Water and Ocean Wind Sensor (WOWS) embodies many of these water cycle objectives. The sensor combines active and passive microwave concepts to provide co-incident and improved measurements of many key oceanic, atmospheric, terrestrial, and cryospheric parameters, now being measured by a variety of separate ongoing and planned space missions. By sharing a 6 m rotating parabolic deployable mesh antenna for active and passive microwave channels from 1.26 to 37 GHz, made feasible by recent advances in antenna technology, WOWS would enhance the spatial resolutions of many parameters. This system would also provide the coincident measurements needed to optimize the retrieval of geophysical parameters, and to characterize the multi-scale and non-linear interaction of the turbulent atmosphere and ocean.

The coincident measurements will provide comprehensive characterization of all the essential terms in hydrologic balance over oceans and the oceanic influence of the cryospheric and terrestrial hydrologic cycles. It has strong potential for being part of, and cost-sharing with, the Global Change Observation Mission (GCOM)-W, which is a series of space missions planned by JAXA, and is part of the constellation of the Global Precipitation Mission (GPM).

While WOWS offers a strong complement of hydrologic observations over oceans, its ranking as a water vapor transport mission was somewhat reduced because (a) it lacks resolved vertical winds, and therefore requires that the transport itself be inferred indirectly over oceans, and (b) transport cannot be inferred over land. This shortcoming is nonetheless mitigated somewhat by the additional capabilities to measure ocean circulation, oceanic evaporation, and air-sea interaction and to map the cryosphere.

Sea Ice Thickness, Glacier Surface Elevation, Glacier Velocity

Mission Summary – Sea Ice Thickness, Glacier Surface Elevation, Glacier Velocity	
Variables	Sea ice thickness; Glacier surface elevation; Glacier velocity
Sensor(s)	Lidar, InSAR
Orbit	LEO, global
Panel Synergies	Climate, Solid Earth

Related RFI(s): ICESAT++ (111), InSAR (83)

Glacier ice and sea ice are other important components of the global water cycle and are highly sensitive to changes in climate. More than three quarters of the freshwater on Earth is stored in the great ice sheets that cover most of Greenland and Antarctica and in glaciers. The dramatic decreases in extent and volume of glacier ice (e.g., Figure 11.2) and sea ice are already having direct effects on society and will have more severe consequences if current warming trends continue.

Two concepts have the potential to provide significant observational improvements of the global distribution of land and sea ice. A combined lidar (e.g., ICESat ++) and InSAR mission as proposed by the Climate, Ecosystems, and Solid Earth panels would aid in monitoring changes in ice sheet elevation, sea ice freeboard and glacier velocity. This mission concept is described in greater detail in Chapter 9.

Groundwater Storage, Ice Sheet Mass Balance and Ocean Mass

Mission Summary – Groundwater Storage, Ice Sheet Mass Balance, and Ocean Mass	
Variables	Ground water storage; Glacier mass balance; Ocean mass distribution
Sensor(s)	Laser ranging
Orbit	LEO, global
Panel Synergies	Climate, Solid Earth

Related RFI(s): GRACE follow-on (GRACE-II) (42), ICESat++ (111)

Water storage is an essential component of the hydrologic cycle and requires knowledge of the water mass stored in aquifers, soil, surface reservoirs, snowpack, ice sheets, and oceans. While GRACE (Gravity Recovery and Climate Experiment, a NASA ESSP mission launched in 2002) has successfully demonstrated the feasibility of space-based gravity measurements for global land hydrology. Even though its relatively coarse spatial resolution (effectively on order of 500 km, although spatial resolution for GRACE has to be interpreted in a manner somewhat different from electromagnetic sensors) has limited its use to large regional-scale observations, breakthrough science has resulted, including observations of seasonal and multi-year variations in mass of the Antarctic and Greenland Ice Sheets. The only way to determine if the multi-year trends are representative of long-term changes in mass balance is to extend the length of the observations. Other hydrological parameters, such as mean river basin evapotranspiration may also be inferred for large river basins (Rodell et al., 2004), but are likewise constrained by the short data record. The somewhat improved spatial resolution of a proposed GRACE Follow On mission (GRACE-II), and the continuation of the observation record would provide invaluable observations of long-term climate related changes in mass of the Antarctic and Greenland Ice Sheets, as well as large Arctic ice caps. Longer records, that would allow better characterization of interannual changes in soil moisture and groundwater storage for use by hydrologists and for use in global land surface models would also result, although the course spatial resolution will continue to be a critical constraint. Other hydrological parameters, such as mean river basin evapotranspiration may also be inferred for large river basins (Rodell et al., 2004). A follow-on GRACE mission would continue the GRACE record of changes in mass of the Antarctic and Greenland Ice Sheets as well as large Arctic ice caps to be measured on a long term and a seasonal basis.

Oceanography is another fertile field for microgravity measurements. Improved knowledge of absolute surface currents from satellite altimetry is expected in the near future with precise measurements of the static geoid (e.g., with the European Gravity Field and Steady-State Ocean Circulation Explorer [GOCE] mission to be launched in 2008). Satellite altimetry cannot distinguish between sea level changes from steric (i.e., temperature and salinity-induced) and from water mass effects. However, this separation is possible by combining altimetry with GRACE, which measures the ocean mass component only. In addition, such a separation allows an independent estimate of glacier melt volume. However, the current GRACE mission has low signal-to-noise ratio over the oceans. GRACE-II would provide more precise estimates of the vertically-integrated ocean mass (or equivalently bottom pressure) variations associated with ocean currents. Data assimilation (from satellite altimetry and GRACE-II) into general circulation models will then allow determination of the vertical structure of the ocean circulation.

Sea level rise is another potential application of microgravity measurements. Precise measurements of sea level rise have been obtained by satellite altimetry for more than a decade. The main contributions to sea level rise are thermal expansion due to ocean warming and water mass input from continental reservoirs (glaciers, ice sheets, and land). GRACE-II would provide a basis for estimating the contribution of land water storage, including the anthropogenic contribution (effects of dams, irrigation, urbanization, deforestation, etc.), to the water budget of large river basins—measurements that currently are not available from any source.

Inland and Coastal Water Quality

Mission Summary – Inland and Coastal Water Quality	
Variables	Inland and coastal water quality; Land use/land cover change
Sensor(s)	Hyperspectral imager, Multispectral thermal sensor
Orbit	LEO or GEO, global or regional
Panel Synergies	Climate, Ecosystems, Health

Related RFI(s): FLORA (38), SAVII (97)

Inland and coastal ecosystems convey many diverse and important benefits to society including food, commercial navigation, waste processing, and recreation. At the same time, a growing body of evidence indicates that these systems are today experiencing major threats from the combined forces of upstream river management, overuse, and pollution (see, e.g., Figure 11.8). These changes are embedding a major human signature inside the global biogeochemical cycles, including modification of thermal regimes, acceleration of nutrient flux, and interception of continental runoff and retention of suspended sediments otherwise destined for the world's oceans. The world's fisheries depend largely on the high productivity of the estuaries and the coastal zones. For most of globe, the state of water quality monitoring and assessment is highly fragmented. In the developed world, individual, focused studies and routine monitoring provide a limited basis for evaluation of water quality status and trends, but our global-scale knowledge based on *in situ* observation has never been adequate, and is in decline. Moreover, these fixed-point measurements do not characterize the interaction of spatial and temporal variability inherent in these complex spatially distributed processes. A major opportunity thus presents itself for remote sensing to fill this strategic information gap.

Two mission concepts are designed to aid in monitoring the overall health of lakes, rivers, reservoirs and coastal regions using indicators such as eutrophication from algal blooms, nuisance plant growth, and increases in temperature. A hyperspectral sensor (e.g., FLORA) combined with a multispectral thermal sensor (e.g., SAVII) in low-Earth orbit (LEO) are part of an integrated mission concept described in Parts I & II which is relevant to several panels, but especially climate. The hyperspectral sensor, with 30 m spatial resolution, would improve mapping capabilities for both algal blooms and sediments. Imaging spectrometry also provides the capability for integrated mapping of land and water properties. Land use/land cover changes can be monitored and used to infer nutrient leaching and sediment transport. The suggested 45 m spatial resolution of SAVII would be effective for high resolution thermal monitoring of many coastal regions and inland water bodies with the exception of smaller lakes and streams. The SAVII multispectral thermal imager would provide the capability for identifying thermal plumes associated with industrial point sources, seasonal runoff, and coastal upwelling, as well as longer-term changes in thermal regimes for lakes, rivers, and reservoirs.

A second mission concept would use a hyperspectral imager in geosynchronous orbit over North America as part of a coastal ecosystems mission concept and is described in greater detail in Chapter 7 (Ecosystems). This sensor would have variable spatial resolution (250 km to 1500 km) and sub-hourly observation time scales. The 350-1050 nm spectral range and 1 nm spectral resolution would provide capability to monitor rapid changes in water quality in coastal regions such as the onset and dynamics of algal blooms and ocean surface eutrophication.

NEXT GENERATION CHALLENGES

In the previous section, we have ranked seven mission concepts that will make key contributions to water cycle science. These missions were ranked primarily on the basis of their potential science contributions and societal relevance, but also on other considerations such as technical readiness. The panel identified several additional observation and estimation challenges that must be addressed, but are not to the point of recommending a specific mission concept. These challenges are described below.

Evaporation

Evaporation from land and ocean surfaces is poorly observed from *in situ* instruments and its climatology is not well known at present. Evaporation is not readily observable using remote sensing. Despite the observation issues, evaporation is central to Earth system science and its constitutive cycles (water, energy, and biogeochemical). Many aspects of climate and weather prediction depend upon accurate determination of these fluxes, as current meteorological products are not advanced enough to provide accurate information. Development of the capability to monitor evaporation directly constitutes a grand challenge for Earth system science.

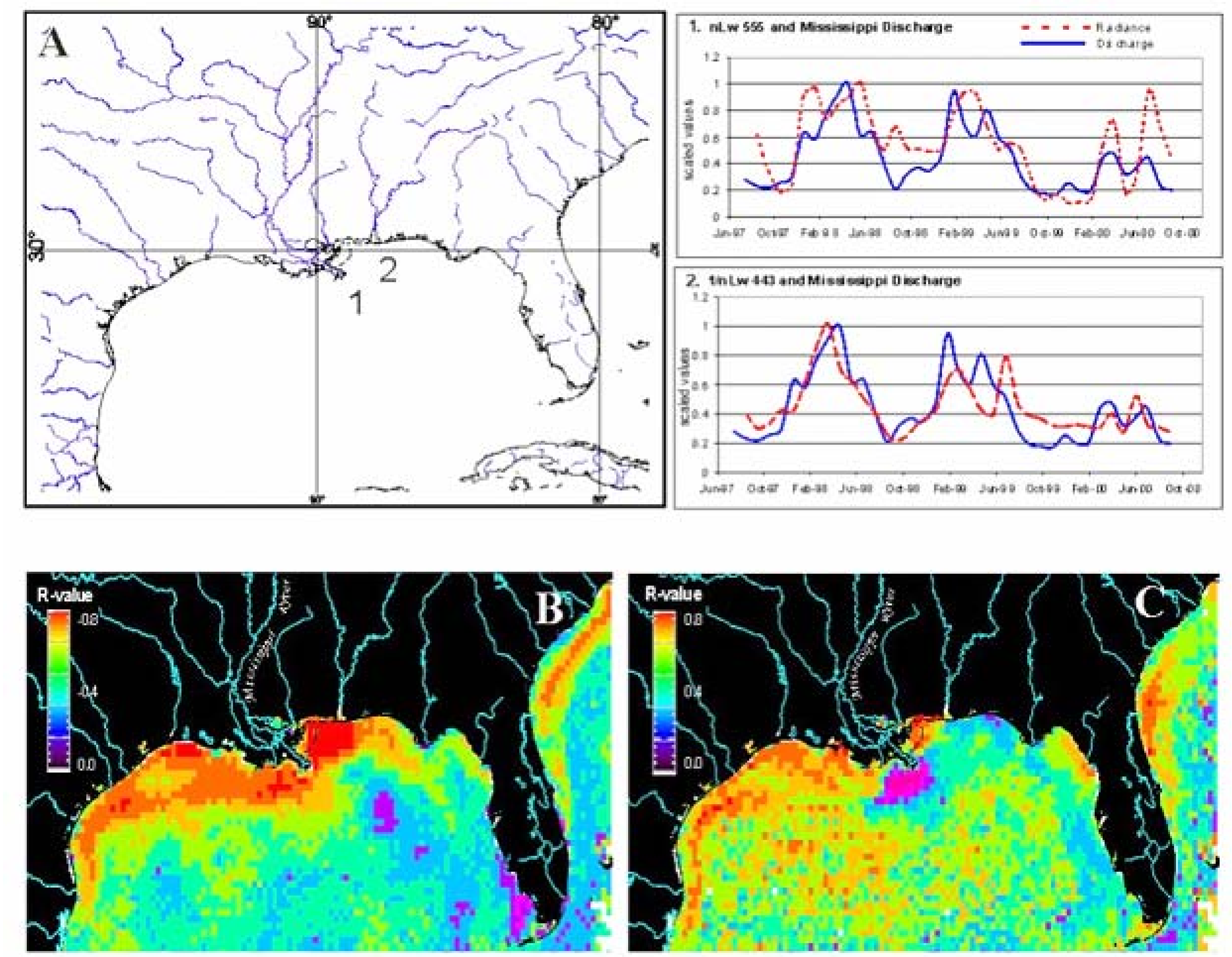

FIGURE 11.8: Rivers transport, process and deliver significant quantities of constituents mobilized by erosion and dissolution of the continental land mass, as well as from pollutants attributable to human activities. The figure shows time series (September 1997-October 2000) of organic matter and sediment near the mouth of the Mississippi River (panel A), and mean organic matter (panel B) and sediment (C) for that interval. SOURCE: Salisbury et al. (2001).

Despite the inability to measure evaporation directly via remote sensing, it nevertheless is possible to measure states and processes that are needed to estimate evaporation. More accurate estimation of evaporation will require a new perspective on how multi-source measurements and models can be combined. The goal should be to facilitate estimation of the diurnal cycle of evaporation over land and ocean surfaces with errors (at temporal resolutions sufficient to resolve the diurnal cycle) of less than 30 Wm^{-2} at 10 km resolution, and over the open ocean with an accuracy of 5 $W m^{-2}$ for a spatial resolution of 1^o (about 100 km). These errors, while still substantial, would be small enough to be comparable to the errors in other terms in the global (and regional) water and energy budgets, and so would facilitate direct estimation of evaporation errors, rather than estimation as a residual term as is often done at present (see Roads et al., 2003 for an example of water and energy budget estimation for the Mississippi River basin).

Under turbulent conditions, evaporation is directly proportional to the latent heat flux (a component of the surface energy balance) and the carbon flux in the surface carbon balance. Evaporation also co-determines—with precipitation—the rate of the global water cycle. The difference of evaporation and precipitation should be zero when globally aggregated, which gives a long-range performance goal for this grand challenge.

The difficulty in measuring evaporation from space is that bulk parameterizations, which are the primary means for estimating evaporation, require knowledge of the near surface specific humidity, a measurement that continues to elude the scientific community. Even space-borne profilers with very high vertical resolution are unable to resolve the boundary layer with the needed precision. Other quantities necessary for estimation of the latent heat flux include the surface wind speed and surface and near-surface temperatures. Over the oceans, surface wind estimates are possible from both active and passive microwave instruments with reasonable accuracy, although under high wind conditions, only scatterometers have proven utility. Over land, direct measurement of surface wind from space is not currently possible. Although not a direct input to the latent heat flux parameterization, the surface temperature is needed to determine saturation vapor pressure at the surface in the case of ocean evaporation, and the actual surface humidity in the case of evaporation over land. Furthermore, the surface and air temperatures together determine the stability of the surface layer, which affects the transfer coefficients used in the calculation of the latent heat flux.

Sea surface and land temperature measurements from a variety of current and planned sensors in both the visible/infrared and microwave wavelengths can provide diurnally-varying values with a relatively high level of accuracy, and a continued mix of space-borne microwave radiometers will continue this record. It should be noted that in addition to the satellite data limitations there are still unresolved issues with the bulk flux parameterizations themselves (Curry et al., 2004).

Remote sensing of land radiometric surface temperature (LST) is critical to all current schemes to estimate evapotranspiration remotely. LST is directly related to the sensible heat component of the energy balance, and is thus inversely proportional to latent energy and evaporation rates. The Bowen ratio (H/LE) is a relatively simple parameter summarizing the relationship between sensible and latent heat flux from a surface. Thermal remote sensing, therefore, can provide an integrated look at land surface evaporation, although overpass timing is critical (mid-afternoon radiant heating of the land surface provides the most useful signal). For some purposes, data from the Geostationary Operational Environmental Satellites (GOES) also can be used to derive LST and surface ET every hour under cloud-free conditions.

Other methods for inferring evaporation can, with a combination of measured and modeled techniques, give some understanding of this flux over large areas. For instance, atmospheric budget analysis using moisture convergence in combination with observed precipitation can be used to estimate evaporation by difference—a technique that is applicable over both land and ocean. Over the oceans, changes in upper ocean salinity combined with oceanic advection can be used to produce an estimate of E-P (global time-varying salinity measurements from Aquarius are expected to greatly improved the basis for estimating space-time fields of E-P over the oceans), In both cases, knowledge of precipitation is necessary—a constraint that is especially limiting over the oceans, and portions of the land where precipitation is poorly observed. Other promising techniques involve the fusion of satellite data with global or regional climate model products. However, the use of these model products eliminates the possibility of comparing the resulting evaporation fields as independent data sources.

Given the inability to measure evaporation directly over large areas (either using *in situ* or remote sensing methods) it is likely that the most significant progress in this area will be in combination with improvements in assimilation into models with improved boundary layer physics. We believe that progress in this area should be a primary focus of the community over the next decade. While it is not possible at present to define a satellite mission that would address the key science questions in this area, several planned satellite missions will have a central role, and should be supported. These include VIIRS aboard NPOESS, which will provide functionality in terms of estimating land and sea surface temperature under clear sky conditions, as well as vegetation information over land, similar to that which currently can be derived from the Terra and Aqua MODIS sensors. A high resolution thermal infrared sensor equivalent to those previously flown on board Landsat satellites would also be useful. Nonetheless, a more focused effort to address the complex problem of how best to combine observations and modeling to produce consistent estimates of ocean and land evaporation is a pressing need, progress on which is essential before observation requirements can be fully specified.

Coordinated Observing Systems

While the panel recognized that the current paradigm is for missions that focus on single primary measurements designed to address a primary science question, perhaps with so-called "secondary science," it also recognizes an alternative paradigm that attempts to address measurements of the water cycle in a more coordinated fashion—e.g., by focusing on a broader set of issues, and attempting to realize synergies associated with multiple, coordinated observations. We outline two such strategies here—one which addresses coordinated measurement of global water cycle variables, and a cloud-aerosol-precipitation initiative.

Integrated Water Cycle Observing System

Society's welfare, progress, and sustainable economic growth, and life itself, depend on the abundance and vigorous cycling and replenishing of water throughout the global environment. The water cycle operates on a continuum of time and space scales and exchanges large amounts of energy as water undergoes phase changes and is moved from one part of the Earth system to another.

A central challenge of a future water cycle observation strategy is to progress from single-variable water cycle instruments to multi-variable integrated water cycle instruments, likely in electromagnetic band families. Experience has shown that the microwave range in the electromagnetic spectrum is ideally suited for sensing the state and abundance of water due to the dielectric properties of the substance. Until now, limits on antenna technology have stymied the harvesting of the synergy that would be afforded by simultaneous multi-channel active and passive microwave measurements. The removal of this roadblock is now possible.

A coordinated water cycle observation strategy will require innovative technology in large microwave antennas that probably will postdate the time frame of this decadal review. However, we view this as an essential element of the technology development needed to support advanced multivariate retrieval methods that can exploit the totality of the microwave spectral information, which will facilitate next generation water cycle observing systems. Nonetheless, it is possibly to see how existing technology, and extensions thereof, would support a multidisciplinary water cycle measurement strategy—e.g., through use of rotating antenna technology as outlined below.

A cross-disciplinary multi-channel active and passive microwave concept would provide co-incident and improved measurements of many key oceanic, atmospheric, terrestrial, and cryospheric parameters. One possibility would be for active and passive microwave channels from 1.26 to 37 GHz to share a large (6 m) rotating parabolic deployable mesh antenna. This appears to be feasible as a result of recent advances in antenna technology, and would have the effect of enhancing the spatial resolutions of many parameters and providing the coincident measurements needed to optimize the retrieval of geophysical parameters. It would also allow characterization of the multi-scale and non-linear interaction of the turbulent atmosphere and ocean.

The mission would be a water cycle and terrestrial biomass observatory. The simultaneous multi-channel active and passive microwave measurements will allow improved-accuracy retrievals of parameters that were the single focus of several explorer-class mission concepts. To be concise, this means that the multiple instruments are not just sharing a spacecraft. Their simultaneous measurements lead to retrievals that are not possible with isolated measurements. Furthermore, the simultaneous monitoring of several of the land, atmospheric, oceanic, and cryospheric states brings synergies that will significantly enhance the understanding of the global water cycle as a system.

A flagship mission based on this concept would combine the following measurements that in the present paradigm constitute individual missions (specific missions indicated where referred to elsewhere in this chapter):

1. Precipitation measurement (GPM follow-on)
2. Ocean wind
3. Soil Moisture and Land Freeze/Thaw Mission (Hydros)
4. Cold-Land Processes Pathfinder (CLPP)
5. Biomass Monitoring
6. Very low frequency subcanopy and subsurface observations (see e.g., discussion of the MOSS RFI in the section "Prioritized Observation Needs")

A shared antenna subsystem would allow many of the requirements outlined in Table 11.2 to be met. It would accommodate the following measurements: scatterometry at P-, L-, C- and Ku-bands and radiometry at L-, C- and X-bands. The measurements would be simultaneous and would have the advantage of a common and steady look-angle. The rotating antenna would facilitate a wide swath for 2- to 3-day repeat coverage.

TABLE 11.2 Elements of an Integrated Water Cycle Observing System

	Science Objective	Science Requirement
SMAP–extended (includes P-band)	Monitor processes that link the water, energy and carbon cycles Monitor vegetation and water relationships over land Extend the capability of climate and weather prediction	Near-surface soil moisture: 4% Volumetric content RMSE in top 2-5 cm soil for vegetation cover < 5 kg/m^2 Root-zone soil moisture: Top 50 cm soil for vegetation cover < 20 kg m/m^2 Land freeze/thaw state: Detect state transition to within 1-2 days
Biomass Monitoring	Monitor above-ground forest biomass and terrestrial stock Estimate changes in terrestrial carbon sources and sinks	Above ground woody biomass: 20% relative accuracy or 1 kg/m^2
SCLP	Support operational weather and water resources applications Study cause and effects of changes in water cycle Develop freshwater inventory	Snow water equivalent: 2 cm RMSE in snowpacks < 20 cm 20% relative in snowpacks > 20 cm
Ocean surface monitoring	Improve weather prediction with high resolution ocean wind speed and direction in all-weather conditions Monitor heat content of oceans and improve air-sea interaction modeling and climate prediction Improve weather prediction and moist processes in models Coastal and open-ocean climate variability and water cycle Extend the capability of climate and weather prediction	Ocean windspeed and direction: 1 m/s and 20 deg Sea surface temperature: 0.5 degrees Celsius Cloud water: 2 mm (land) 0.1 mm (ocean) Rain rate: 5 mm/hr Snow water equivalent: 3 cm Sea surface salinity: 0.2 psu

Because the antenna subsystem would be shared, the instrument cost would not scale with the number of scatterometer and radiometer channels. Total mission cost would probably be in the $700 million to $1 billion range, which while considerably larger than any of the individual component measurements, would represent a substantial savings relative to the sum of the costs for stand-alone missions for each of the elements. The cost is end-to-end with 30 percent reserves and for 5 years of operation. The instruments would share a single 6 m light-weight deployable mesh reflector capable of supporting multiple frequencies up to Ku-band. The sharing of elements of the antenna and digital subsystems results in significant cost-savings.

In order to reap the benefits of the synergy some trade-offs need to be made with respect to the constitutive explorer-class mission. The principal one is to trade some resolution loss with gains in revisit as well as multi-channel observations. This trade particularly affects biomass and snow, and deep soil moisture (P-band). However, since carbon biomass, deep soil moisture, and snow pack are slowly varying in time, it may be possible to regain the resolution by combining multi-temporal passes. On the other hand, the multi-channel approach affords advantages to some constituent retrievals—for instance, simultaneous retrieval of vegetation biomass would improve soil moisture retrieval by avoiding the need for auxiliary vegetation information. It should be noted that because altimetry, although based on radar, uses SAR rather than scatterometry, such a system would not monitor surface water stage and surface area (hence volume) or river slopes. It should also be noted that one shortcoming of shared antenna systems is that the entire system is susceptible to complications with any of individual instruments—i.e., the cost savings are achieved by accepting the risk of multi-instrument "slippage," as has been the case with NPOESS.

Cloud–Aerosol–Precipitation Initiative

> As an orange cloud formed as a result of a dust storm over the Sahara and, caught up by air currents, reached the Philippines and settled there with rain, I understood that we are all sailing in the same boat.
>
> —*Vladimir Kavalyonok, USSR cosmonaut*
> *(see Figure 11.9).*

One of the key uncertainties in the areas of weather, climate, and the fresh water supply remains the processes that govern the interaction among aerosols, clouds and precipitation. The need to better understand these processes has been articulated by a number of studies, including the Intergovernmental Panel on Climate Change's report "Climate Change 2001: The Scientific Basis" (IPCC, 2001), the Strategic Plan for the U.S. Integrated Earth Observation System (IWGEO, 2005), and the U.S. Climate Change Science Program for Fiscal Years 2006 and previous years (CCSP, 2005). Since aerosols serve as nuclei for cloud particles and affect their growth to precipitation size particles—as well as influencing the opacity of clouds to sunlight—the close interaction among these processes is evident.

The main objective of an integrated Cloud-Aerosol-Precipitation mission would be to provide a more quantitative basis for predicting changes to the planet's hydrological cycle and energy balance as a step toward prediction of severe weather, climate and climate change with much higher confidence than now exists. The cloud-aerosol-precipitation climate problem is, however, complex. Progress will likely require a coordinated combination of multiple observational and theoretical techniques, platforms and vantage points, and strategies that explicitly plan for integration of these different components. The rewards, however, are also extremely high, leading to advances in areas of air pollution and human health; availability of fresh water; prediction of weather and extreme events; aerosol effects on climate; and cloud influences on climate.

Portions of the space-based component of a coordinated observation plan along these lines were articulated in various RFI responses dealing with cloud-aerosol, aerosol-precipitation and cloud-aerosol-precipitation. This mission concept and package would involve the possible addition of instruments to approved missions (e.g., GPM, NPOESS). Additional assets such as a new High Spectral Resolution lidar for aerosol detection and analysis combined with multi-frequency Doppler radar for cloud content and vertical motions are required. Tropospheric wind observations would also be needed to help separate the effect of atmospheric motions from the effects of aerosol concentrations. This will be addressed in part by the ACE mission concept (Parts I & II), but is referred to here as an initiative because the complexity of the problem requires careful coordination of the ACE mission with other proposed missions, such as Wind Lidar (3D-Winds in Parts I & II) and potential international contributions (e.g. EarthCARE and potential follow-ons).

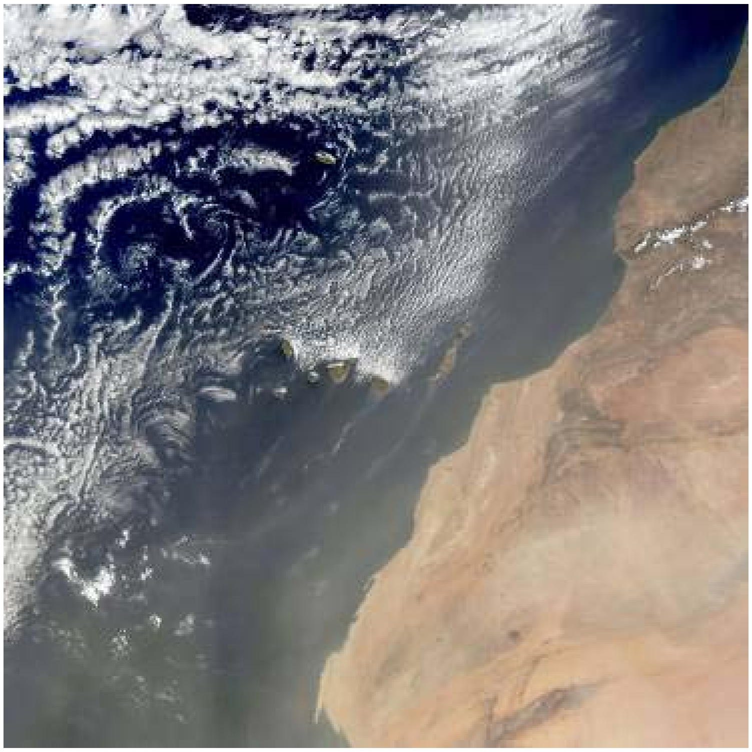

FIGURE 11.9: Saharan dust storm of July 24, 2003 showing dust cloud the Atlantic Ocean and the Canary Islands off northwest Africa, as captured by NASA's MODIS instrument on the Terra satellite. SOURCE: www.gsfc.nasa.gov/feature/2004/0116dust.html).

A coordinated cloud-aerosol-precipitation initiative requires close coordination among the weather, climate, and water communities. International cooperation, most specifically with Japanese and European scientists and agencies would be needed to bring such an initiative to fruition. A working group to plan and coordinate the addition of targeted observations to future missions should be established immediately in order to bring this grand challenge in Earth Sciences to bear in the 2015-2025 timeframe. The above initiative—which would involve multi-frequency Doppler radars, high spectral resolution lidars, wind lidars and radiometers—would be expensive. It should not be envisioned as a stand-alone mission concept, but rather as an "initiative" that would enable the systematic planning among national and international agencies to bring the measurement concept to fruition. By systematic leveraging of assets approved for other missions, the Cloud-Aerosol-Precipitation initiative would focus mostly on optimizing (and coordinating) planned missions, rather than on new launches. The complexity of the problem, and the great wealth of potential assets in the form of planned missions globally, require that this effort be undertaken by a body more formal than an ad-hoc group of interested scientists.

End-to-end Information System Needs

Managing the next generation of satellite data will be more challenging, and user requirements much greater, than today. Global water cycle information must be synthesized from a wide variety of sensors—optical, thermal, passive and active microwave, polar orbiting, geostationary, etc. Some of these data must be delivered in real time, especially for weather forecasting and flood warnings. Other data must be archived stably to allow retrieval for analysis of climate trends over many decades. Additionally, critical *in situ* information such as streamflow, snowpack, and lake/reservoir stage data must be integrated with the satellite data for optimum interpretation and policy analysis.

Scientifically, it is most valuable to have water cycle data harmonized and accessible from one (possibly virtual) location, and at multiple time and space resolutions. For instance, one cannot understand or forecast runoff trends, including floods, without first knowing precipitation. Lead responsibility for observing various aspects of the water cycle crosses NASA, NOAA, USGS, and USDA. Building and sustaining integrated hydrologic datasets for the U.S. will require coordination among these agencies that while technologically feasible, in fact does not yet exist—notwithstanding ongoing efforts like the Corporation of Universities for the Advancement of Hydrologic Science (CUAHSI) Hydrologic Information System "WaterOneFlow" web services enterprise.

While NASA may have responsibility only for delivering the satellite-based data stream, the above-named agencies collectively have responsibility for building the coordinated data system that an integrated hydrologic forecast model requires. Furthermore, while some of the measurements needed to understand and predict water cycle changes are included in the observation system that supports global weather forecasts (e.g., NPOESS), those measurements that have demonstrated potential for research and applications will need to be sustained (see the section "Prioritized Observation Needs") to monitor trends and to allow the development of prediction schemes. One or more of the above agencies will need to be responsible for sustaining the observations beyond the single proposed missions.

Global hydrologic information provides even a greater challenge, particularly because *in situ* datasets are the property of individual nations and are generally less openly available than is the case in the U.S. (IAHS 2001). Because water is an economic commodity, cross-border water jurisdiction issues require international datasets. Satellite data are the only unbiased repeatable measure available from some countries, and so are exceptionally valuable for global hydrologic studies. As U.S. scientists must rely more on foreign satellites for data, sharing global datasets will be essential for scientific progress.

SUMMARY

Water is central to life on Earth, but there remain substantial gaps in our understanding of the location of stored water, and the processes that control its movement. Better understanding of water cycle science would have not only important science benefits, but would also benefit society by facilitating more effective management of this renewable resource. Yet better understanding of the global water cycle will require new and more comprehensive measurements which are feasible only through a combination of remote sensing and *in situ* observations. We view the imperative for future water cycle missions to be the ability to address both scientific and societal challenges. The scientific challenge, in our view, is to integrate *in situ* and space borne observations to quantify the key water cycle state variables and fluxes. The centerpiece of this vision will be a series of Earth observation missions that will measure the states, stocks, flows and residence times of water on regional-to-global scales, followed by a series of coordinated missions that will address the processes, on a global scale, that underlie changes in the state parameters. The accompanying *societal challenge* is to make better use of water data produced by *in situ* and remote sensing missions to manage water resources more effectively.

The four highest ranked water cycle missions proposed in this chapter would contribute greatly to the science and societal goals associated with water. The approved *GPM* mission is recommended to be launched without further delay. It will provide diurnal estimates of precipitation at a spatial resolution sufficient to resolve major spatial variations over land and sea. A *soil moisture* mission (Soil Moisture Active/Passive, or SMAP in Parts I & II) would provide estimates of soil moisture over most of the globe. Soil moisture is a key term in the land surface water balance which controls land-atmosphere fluxes over many parts of the globe (in particular, recycling of moisture from the land to the atmosphere), and is a key variable that affects the response of runoff to precipitation and hence is critical for flood and drought prediction. A *surface water* mission (a generalization of which is SWOT—Surface Water/Ocean

Topography in Parts I & II) would provide observations of the variability of water stored in lakes, reservoirs, wetlands, and river channels, and would support estimates of river discharge. It would also provide critical information necessary for water management, particularly in international rivers. A *cold season* mission would estimate the water storage of snowpacks, especially in spatially heterogeneous mountainous regions that are the source areas for many of the world's most important rivers.

Taken together and in coordination with *in situ* and airborne sensors, these four missions would form the basis for a coordinated effort to observe the terrestrial surface water cycle globally. However, building and sustaining integrated hydrologic datasets for the U.S. will require close coordination among many federal agencies, as well as a commitment to sustaining the observations beyond the single proposed missions.

In addition to measurements that would be made by these four missions, several other measurements that would benefit analyses of the water cycle were highly rated by the water cycle panel, albeit below the four identified above. These include missions that would estimate water vapor transport, sea ice and glacier mass balance, groundwater and ocean mass, and inland and coastal water quality (see Table 11.1). These measurements and water cycle issues are discussed in the section "Prioritized Observation Needs." Some of these measurements have direct relevance to the needs of other panels and that synergy was considered in the selection of the integrated missions recommended in Parts I & II.

The panel identified several "next generation" observation and estimation challenges that must be addressed, but need additional time for technology development. These included development of the capability to monitor evaporation directly from space, and creation of coordinated observing systems. Two examples of the latter might be a global water cycle system to "simultaneously" measure precipitation, ocean wind, soil moisture and land freeze/thaw, snow water equivalent, biomass, and the subsurface; and a cloud-aerosol-precipitation initiative.

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APPENDIX 11.1
Water Cycle-relevant RFIs Examined by the Panel

RFI Index Number	RFI Title	Comment
2	SIRICE	Submillimeter Infrared Radiometer Ice Cloud Experiment (SIRICE): Daily Global Measurements of Upper Trop. Ice Water Path and Ice Crystal Size
5	ATOMMS	Active Temperature, Ozone, and Moisture Microwave Spectrometer:Constellation of small satellites to provide high vertical resolution moisture, ozone, temperature and pressure measurements in troposphere and middle atmosphere
9	ARIES	Atmospheric Remote-Sensing and Imaging Emission Spectrometer: Observe the infrared spectrum from 3.6 to 15.4 μm at high-spatial resolution ≥ 1x1 km globally. Both of these features are critical for the study of the hydrology cycle and for understanding the water vapor feedback
13	CHARMS	Cloud Height and Altitude-Resolved Motion Stereo-imager
14	CHASM	Cloud Hydrology and Albedo Synthesis Mission: Mission to measure the water content of clouds, concurrently with their albedo and cloud-top height.
17	Climate Scope Reanalysis Mission Concept	A mission to produce, validate, and disseminate physically consistent climate research quality datasets from separate missions and satellite platforms
19	CLPP_	Cold Land Processes Pathfinder: Advanced Space-based Observation of Fresh Water Stored in Snow
21	COCOA	Coastal Ocean Carbon Observations and Applications: Integrated observations (hyperspectal from GEO) and models to discriminate and quantify particulate and dissolved carbon species in coastal waters, as well as the exchanges of carbon between the land, atmosphere, and ocean.
23	C-CAN	Continuous Coastal Awareness Network will measure sea surface height, coastal currents and winds and sea spectral reflectance from different Earth vantage points at high spatial and/or temporal resolution
25	Daedalus	Daedalus: Earth-Sun Observations from L1: Simultaneously observe key solar emission/space weather parameters and spectrally resolved radiances over the entire illuminated Earth to characterize the direct influence of solar variability on the Earth System
27	WOWS	Water and Ocean Wind Sensor using active and passive microwave concepts
36	Emery CU Surge	"GPS to measure ocean wind speed/direction, sea surface height and land surface soil moisture"
38	FLORA	Global, high spatial resolution measurements of vegetation composition, ecosystem processes and productivity controls, and their integrated responses to climate
42	Grace Follow-on Mission	GRACE follow-on
44	GISMO	Glaciers and Ice Sheets Mapping Orbiter
46	Global Water Resources Mission	An international effort consisting of about two dozen satellite systems, each of which is comparable with current operational GEO and LEO satellites

RFI Index Number	RFI Title	Comment
49	GPS-HOT	High resolution/high temporal revisit oceanography mission for mesoscale process characterization, will also yields data suitable for global tsunami warning
50	H_2S Ocean Emissions	H_2S emitting from ocean surface
55	Human-Induced Land Degradation	Detecting Human Induced Land Degradation Impact on Semi-Arid Tropical Rainfall Variability. Uses satellite-derived precipitation data, satellite-derived vegetation index data (no apparent observation program proposed)
56	Hydros	Hydrosphere Mapper: Radar interferometry system to make high-resolution measurement of the surface of the ocean and water bodies on land
61	CAMEO	Composition of the Atmosphere from Mid-Earth Orbit
62	OOLM	Operational Ocean and Land Mission: Wide swath ocean altimeter, and C- or C-band SAR, plus Visible/Infrared Imaging Spectrometer on two satellites, for various (primarily ocean/coastal) needs
66	Claim 3-D Mission	Satellite mission to advance understanding of cloud and precipitation development by measuring vertically resolved cloud microphysical parameters in combination with state of the art aerosol measurements
67	MATH	Monitoring Atmosphere Turbulence and Humidity
70	MOSS	The Microwave Observatory of Subcanopy and Subsurface is a synthetic aperture radar (SAR) operating at the two low frequencies of 137 MHz (VHF) and 435 MHz (UHF) with the primary objective of providing measurements for estimation of global soil moisture under substantial vegetation canopies (200 tons/ha or more of biomass) and at useful soil depths (2-5 meters).
71	GeoCarb Explorer	GEOCarb mission will provide continent-wide measurements of ecosystem carbon and water dynamics with multiple observations per day
72	Multiplatform InSAR	Forest Subcanopy Topography and Soil Moisture
74	Suborbital Earth System Surveillance	UAVs to be used for synoptic weather, hurricanes, air quality, stratospheric ozone, ozone depleting substances, greenhouse gases, ice sheets, forest fires, droughts, and storm damage
76	Far IR	Far-Infrared for understanding natural greenhouse effect, atmospheric cooling by water vapor, and the role of cirrus clouds in climate
79	Integrated Water Cycle Observations	Coordinated water cycle observations from space
80	Low-Cost Multispectral Earth Observing System	Global land observation system that enhances Landsat and OLI with stereo multispectral imaging, greater coverage, revisit (eight days and better), and higher resolution
82	Surface Uncertainty	Surface Shortwave and Longwave Broadband Network Observation Uncertainty for Climate Change Research
83	InSAR	InSAR from orbital platform, in particular to produce spatially continuous maps of ground displacements at fine spatial resolution, for natural hazards science and applications
86	OCEaNS	Ocean Carbon, Ecosystem and Near-Shore Mission designed to advance quantification of ocean primary production, understanding of carbon cycling, and capacity for predicting ecosystem responses to climate variability
87	OLOM	Ocean and Land Operational Mission: Similar to OOLM (line 38) except that second satellite would carry a 2 frequency Delay-Doppler Altimeter and a Water Vapor Radiometer rather than WSOA

RFI Index Number	RFI Title	Comment
88	Our Vital Skies	Program to address scientific questions at the interface between aerosol, cloud and precipitation research using combination of in situ and space-based observations
90	Polar	Polar Environmental Monitoring, Communications, and Space Weather from Pole Sitter Orbit
91	ABYSS	Radar altimeter for bathymetry, geodesy, oceanography
92	GPS RO	Contributions of Radio Occultation Observations to the Integrated Earth Observation System
97	SAVII	Spaceboarne Advanced Visible Infrared Imager Concept: Hyperspectral measurements in vis-near IR; multispectral measurements in short wave infrared, and multispectral measurements in thermal infrared for vegetation studies, changes in surface cover and composition, and thermal monitoring
99	SH2OUT	Sensing of H2O in the Upper Troposphere
100	GPM	Global Precipitation Mission
103	Surface Observatories in Support of Observations of Aerosols and Clouds	Surface observations of water vapor, temperature, and winds, plus surface radiative fluxes and cloud and aerosol properties
104	Terra-Luna	Earth-Moon science mission that would provide Earth measurements over a relatively short period during Earth-orbiting phase, revisited at intervals of a decade or so, including boreal and tropical forest land cover and biomass mapping, global ocean eddies, coastal currents and tides, and land cover and canopy height
107	Water Vapor Monitoring Missions	
108	WatER	The Water Elevation Recovery Satellite Mission
110	Climate-Quality Observations from Satellite Lidar	Lidar measurements to address the themes of climate variability and change, weather, and water resources and the global hydrologic cycle
111	Advanced ICESat	Ice Cloud and land Elevation Satellite

NOTE: A complete index of RFI responses is provided in Appendix E. Full-text versions of the responses are available on the compact disc that accompanies this report.

Appendixes

A
Statement of Task

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

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

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

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

B
Acronyms and Abbreviations

ABBA	Automated Biomass Burning Algorithm
ABI	Advanced Baseline Imager
ABYSS	Altimetric Bathymetry from Surface Slopes
ACE	Aerosol/Cloud/Ecosystem
ACRIM	Active Cavity Radiometer Irradiance Monitor
ADM	Atmospheric Dynamics Mission
AERONET	Aerosol Robotics Network
AIRS	Aerometric Information Retrieval System or Atmospheric Infrared Sounder
ALOS	Advanced Land Observing Satellite
ALT	Radar Altimeter
AMSR-E	Advanced Microwave Scanning Radiometer- Earth Observation System
AMSU	Advanced Microwave Sounding Unit
AOD	Aerosol Optical Depth
APS	Advanced Polarimetric Sensor
AQI	Air Quality Index
ARM	Atmospheric Radiation Measurement
ASCAT	Advanced Scatterometers
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days and Seasons
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATLS	Across Trophic Level Systems
ATMS	Advanced Technology Microwave Sounder
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
AVHRR	Advanced Very High Resolution Radiometer
BRDF	Bidirectional Reflectance Distribution Function
CABS	Center for Applied Biodiversity Science
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations

CCSP	Climate Change Science Program
CDC	Centers for Disease Control and Prevention
CDOM	Colored Dissolved Organic Matter
CDR	Climate Data Record
CERES	Clouds and the Earth's Radiant Energy System
CESDU	Committee on Environmental Satellite Data Utilization
CFC	Chlorofluorocarbon
CHAMP	Coral Health and Monitoring Project or Challenging Minisatellite Payload
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CLIVAR	Climate Variability and Predictability
CLPP	Cold Land Processes Pathfinder
CMDL	Climate Monitoring and Diagnostics Laboratory
CME	Coronal Mass Ejection
CMIS	Conical-Scanning Microwave Imager/Sounder
CNES	Centre National d'Etudes Spatiales
C/NOFS	Communication/Navigation Outage Forecasting System
CONNTRO	Committee on NASA-NOAA Transition from Research to Operations
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
COSPAR	Committee on Space Research
CPR	Cloud Profiling Radar
CrIS	Cross-track Infrared Sounder
CRYSTAL FACE	Cirrus Regional Study of Tropical Anvils and Cirrus Layers–Florida Area Cirrus Experiment
CTM	Chemical Transport Models
CUAHSI	Corporation of Universities for the Advancement of Hydrological Sciences
CZCS	Coastal Zone Color Scanner
DESDynI	Deformation, Ecosystem Structure, and Dynamics of Ice
DIAL	Differential Absorption Lidar
DMSP	Defense Meteorological Satellite Program
DOC	Dissolved Organic Carbon
DoD	Department of Defense
DOE	Department of Energy

DSCOVR	Deep Space Climate Observatory
DWL	Doppler Wind Lidar
ECMWF	European Centre for Medium-Range Weather Forecasts
EDR	Environmental Data Record
ENSO	El Niño Southern Oscillation
ENVISAT	Environmental Satellite
EOS	Earth Observing System
EPA	Environmental Protection Agency
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite
ERS	European Remote-Sensing Satellites
ESA	European Space Agency
ESAP	Earth Science Applications Pathfinder
ESAS	Earth Science and Applications from Space
ESEI	Extended Special Events Imager
ESSP	Earth System Science Pathfinder
ESTO	Earth Science Technology Office
EUV	Extreme Ultra-Violet
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FOV	Field of View
FY	Fiscal Year
GACM	Global Atmospheric Composition Mission
GARP	Global Atmospheric Research Program
GCM	Global Climate Models
GCOS	Global Climate Observing System
GDP	Gross Domestic Product
GEO	Geostationary Earth Orbit
GEO-CAPE	Geostationary Coastal and Air Pollution Events
GeoSAR	Geographic Synthetic Aperture Radar
GEOSS	Global Earth Observing System of Systems

GIFTS	Geostationary Imaging Fourier Transform Spectrometer
GLONASS	Global Navigation Satellite System
GNSS	Global Navigating Satellite System
GOCE	European Gravity Field and Steady State Ocean Circulation Explorer
GOES	Geostationary Operational Environmental Satellite
GOES-R	Geostationary Operational Environmental Satellite-R (the next generation of GOES satellites)
GOME	Global Ozone Monitoring Experiment
GPM	Global Precipitation Measurement (mission)
GPS	Global Positioning System
GPSRO	Operational GPS Radio Occultation
GRACE	Gravity Recovery and Climate Experiment
GSFC	Goddard Space Flight Center
HAB	Harmful Algal Bloom
HAZUS	Hazards US
HDWL	Hybrid Doppler Wind Lidar
HES	Hyperspectral Environmental Sensor
HPS	Hantavirus Pulmonary Syndrome
HSB	Humidity Sounder for Brazil
HyspIRI	Hyperspectral Infrared Imager
IAHS	International Association of Hydrological Sciences
IASI	Infrared Atmospheric Sounding Interferometer.
IBEX	Interstellar Boundary Experiment
ICESat	Ice, Cloud, and Land Elevation Satellite
ICSU	International Council for Science
IEOS	International Earth Observing System
IIP	Instrument Incubator Program
InSAR	Interferometric Synthetic Aperture Radar
IORD-II	Integrated Operational Requirements Document II
IPCC	Intergovernmental Panel on Climate Change
IPO	Integrated Program Office
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project

JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
Ladar	Laser Radar
LDCM	Landsat Data Continuity Mission
LEO	Low Earth Orbit
Lidar	Light Detection and Ranging
LISA	Laser Interferometer Space Antenna
LIST	Lidar Surface Topography
LSCE	Laborotoire des Sciences du Climat et de l'Environnement
LST	Land Radiometric Surface Temperature
LTER	Long Term Ecological Research
LVIS	Laser Vegetation Imaging Sensor
MODIS	Moderate-Resolution Imaging Spectrometer.
MEO	Medium Earth Orbit
MetOp	Meteorological Operational Satellite Program
MLS	Microwave Limb Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
MOSAIC	Measurement of Ozone by Airbus In-service Aircraft
MOSS	Microwave Observatory of Subcanopy and Subsurface
MSS	Multispectral Scanner
MSU	Microwave Sounding Units
MTPE	Mission to Planet Earth
MTSAT	Multi-Function Transport Satellite
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (of Japan)
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NEON	National Ecological Observatory Network
NESDIS	National Environmental Satellite, Data and Information Service
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration

NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Program
NPS	National Park Service
NRC	National Research Council
NSA	National Snow Analysis
NSB	National Science Board
NSCAT	NASA Scatterometer
NWP	Numerical Weather Prediction
OCO	Orbiting Carbon Observatory
OLI	Operational Land Imager
OMI	Ozone Monitoring Instrument
OMPS	Ozone Monitoring and Profiling Suite
OOLM	Operational Ocean and Land Mission
ORION	Ocean Research Interactive Observatory Networks
OSTM	Ocean Surface Topography Mission
OSTP	Office of Science and Technology Policy
OVWM	Ocean Vector Winds Mission
PARAGON	Progressive Aerosol Retrieval and Assimilation Global Observing Network
PARASOL	Polarization & Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PATH	Precipitation and All-Weather Temperature and Humidity
PBL	Planetary Boundary Layer
POLDER	Polarization and Directionality of the Earth's Reflectances
RADARSAT	Radar Satellite
RAOB	Rawinsonde Observation
RASS	Radio Acoustic Sounding System
RCTRO	Radiance Calibration and Time Reference Observatory
RFI	Request for Information
RMP	Risk Management Plan
RMSE	Root Mean Square Error
RO	Radio Occultation
RVF	Rift Valley Fever

SAC-C	Satelite de Aplicaciones Cientificas-C
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communication
SAVII	Spaceborne Advanced Visible Infrared Imager
SCIAMACHY	Scanning Imaging Absorption SpectroMeter for Atmospheric ChartographY
SCLP	Snow and Cold Land Processes
SeaWiFS	Sea-viewing Wide Field of View Sensor
SESWG	Solid Earth Sciences Working Group
SIM	Spectral Irradiance Monitor
SIRCUS	Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources
SLC	Scan Line Corrector
SLR	Satellite Laser Ranging
SMAP	Soil Moisture Active-Passive
SMD	Science Mission Directorate
SMMR	Scanning Multichannel Microwave Radiometer
SNOTEL	Snowpack Telemetry
SORCE	Solar Radiation and Climate Experiment
SPARCLE	SPAce Readiness Coherent Lidar Experiment
SPOT	Satellite Probatoire de l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SSMI	Special Sensor Microwave Imager
SSO	Sun-Synchronous Orbit
SST	Sea Surface Temperature
STEREO	Solar Terrestrial Relations Observatory
SVAT	Soil Vegetation Atmosphere Transport
SWE	Snow Water Equivalent
SWIR/IR	Short-wave Infrared/Infrared
SWOT	Surface Water and Ocean Topography
TAO	Tropical Atmosphere Ocean
TEC	Total Electron Content
TES	Tropospheric Emission Spectrometer

TIM	Total Irradiance Monitor
TIROS-N	Television Infrared Observation Satellite-N
TOGA	Tropical Ocean-Global Atmosphere Program
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TOPSAR	Topographic Synthetic Aperture Radar
TRMM	Tropical Rainfall Measuring Mission
TSIS	Total Solar Irradiance Sensor
UAV	Unmanned Aerial Vehicles
UHF	Ultra High Frequency
ULDB	Ultra-long Duration Balloons
UMBC	University of Maryland Baltimore County
UNDP	United Nations Development Programme
USAID	United State Agency for International Development
USDA	United States Department of Agriculture
USGCRP	United State Global Change Research Program
USGS	United States Geological Survey
VBZ	Vector-borne and Zoonotic
VCL	Vegetation Canopy Lidar
VIIRS	Visible Infrared Imager Radiometer suite
VLBI	Very Long Baseline Interferometry
VOC	Volatile Organic Chemicals
WF-ABBA	Wildfire Automated Biomass Burning Algorithm
WMO	World Meteorological Organization
WOCE	World Ocean Circulations Experiment
WOWS	Water and Ocean Wind Sensor
WRSI	Water Requirement Satisfaction Index
WSOA	Wide Swatch Ocean Altimeter
WTC	World Trade Center
XBT	Expendable Bathythermograph
XOVWM	Extended Ocean Vector Winds Mission

C
Blending Earth Observations and Models—The Successful Paradigm of Weather Forecasting

PART I

The development of modern operational weather forecasting, founded on scientific understanding, global observations, and mathematical computer models, is one of the great success stories of Earth Science, and offers a paradigm for the use of Earth observations in many other applications of benefit to society. This section describes how observations are used in models and in data-assimilation systems to produce diagnostic status-assessments and forecasts and illustrates why observations of different variables (e.g., temperature and winds) and different types of observations of the same variable (e.g., temperature) are valuable. It goes without saying that direct study of observations is central for many scientific investigations and applications.

Part II of this appendix illustrates the wide diversity of *in situ* and satellite observations for operational meteorology and oceanography. The improvements in the observing systems over recent decades have contributed substantially to improvements in scientific knowledge, to valuable improvements in forecast capability on short (1-3 day) and medium-range (3-10 days) time scales, and have made possible the creation of new forecast capabilities for variations in the ocean-atmosphere on time scales of months to years such as ENSO (El Niño-Southern Oscillation).

Blending Earth Observations and Models

The global era of numerical weather prediction began with the 1979 Global Weather Experiment (GWE), which provided unprecedented and comprehensive observations of the global atmosphere for an entire year, using *in situ* and satellite data, for the purposes of scientific investigation and to determine the limits of atmospheric predictability. Many elements of the GWE observation programme, both satellite and *in situ*, have continued as operational programs since 1979. Joint use of the satellite and *in situ* data for diagnostic and prediction purposes posed substantial scientific challenges that were not satisfactorily resolved in operational practice until the mid-1990s with the development of four-dimensional variational data assimilation systems.

The scientific challenges of using both satellite and *in situ* data included the fact that the satellite data are measurements of outgoing radiation at satellite level which have a complicated dependence on multiple aspects of atmospheric structure, whereas *in situ* data typically provide a direct measurement of one aspect of atmospheric structure. Moreover, the satellite data provide a continuous stream of data along a swath below the satellite orbit, but may not exactly reproduce its view of a particular point for many hours, or perhaps several days. In addition, depending on the viewing geometry and frequency band used by a satellite instrument, both clouds and precipitation may limit observational capability. Furthermore, satellite and *in situ* data have very different error characteristics, which also complicate the inference of information.

Optimal estimation of the evolving state of the atmosphere over a period of time (say, one day) requires one to use not only the observations available within that time window, but also earlier observations, together with knowledge of the laws governing atmospheric evolution. The evolution laws are highly nonlinear and are expressed in the forecast equations of an atmospheric model. To begin the interpretation of the observations received between 1200 UTC yesterday and 1200 UTC today, one projects yesterday's best estimate at 1200 UTC forward in time to 1200 UTC today using the forecast model, to provide an *a priori* estimate for calculation of today's best estimate. The evolving *a priori* state is sampled through the 24 hours by a simulated observation network to provide the *a priori* estimate of the actual observations. The estimate of the observations (i.e., the expected values of the observations) includes simulations of the actual *in situ* observations and simulations of the observations of the actual fleet of satellites operating during the period.

The mismatch between the actual observations and expected observations (simulated from the *a priori* forecast) are used in an iterative variational procedure to adjust the starting point for the forecast so that the trajectory of the forecast (i.e., the evolving model state) becomes increasingly close to the observations. The iterative nature of the calculation has many advantages, not least that one can make accurate use of observations which are nonlinear in the model variables, and that many different types of observations can contribute to the estimation problem. The algorithm is known as four-dimensional variational data assimilation (4D-Var) and the underlying Bayesian inference theory is closely related to algorithms such as the Kalman filter. The substantial computer costs are justified by the benefits of the calculation. A prime output of the calculation is the best estimate of the atmospheric state at 1200 UTC today. However there are many other benefits, not least a systematic resource for determining random and systematic errors in the observations, in the model, and in the procedure itself.

Current practice in operational data assimilation has evolved to its present state for two important reasons. The first reason is that the observations available at 1200 UTC today cannot provide a global picture, because of gaps in the spatial coverage (both in the horizontal and in the vertical), gaps in temporal coverage, gaps in the range of observed variables, and uncertainties and variations in the errors and sampling characteristics of different observing systems. The numerical model uses yesterday's best estimate, and observations taken within the assimilation window, to fill the observational gaps by transporting information from data rich to data sparse areas. The second reason for the present approach is related to a basic result in estimation theory. Suppose one seeks a best estimate of the state of a system using two sources of information, with accuracies[1] represented by $\mathbf{A_1}$ and $\mathbf{A_2}$. Theory tells us that in the best combination of the two estimates, the two sources of information are weighted by their accuracies, and the accuracy $\mathbf{A}$ of the resulting combination is given by

$$\mathbf{A} = \mathbf{A_1} + \mathbf{A_2}$$

Two important implications follow:

1. The information in the statistical combination of the two sources of information is more accurate than either source alone, i.e., the accuracy of the overall estimate, A is greater than either A_1 or A_2.
2. An increase in accuracy of either source of information will improve the accuracy of the combined estimate.

Both implications are valid whether the information in $\mathbf{A_1}$ and $\mathbf{A_2}$ come from different measurements made in the assimilation window, or from earlier measurements projected forward in time using the numerical model. Since in well-observed areas, the accuracy of the 24 hour forecast is comparable to the observation accuracy on the scales resolved by model, one gets the well-established result that <u>the accuracy of the best estimate provided by the data assimilation process is higher than the accuracy of either the observations alone or the forecast alone.</u> A vital feature of the diagnostic data-assimilation products is that they are multi-variate, and therefore satisfy the natural requirements for dynamic, thermodynamic, and chemical consistency.

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[1] Technically, the accuracy of an observation is given by the inverse of an error covariance matrix associated with the observation, which is a measure of the error or uncertainty of the observation and how the errors are correlated spatially.

The sequence of best estimates derived in this way can be generated with any desired time-resolution, from hourly to 3-hourly, 6-hourly, 12-hourly, and 24-hourly. The sequence of best estimates of global atmospheric distributions of trace-constituents, dynamical fields (winds, pressures), and thermodynamic fields (temperatures, radiation, clouds rainfall turbulence intensity) are a key product for many *diagnostic and status-assessment* products. The latest product in the sequence, the best estimate for 1200 UTC today in our example, is a key product for the production of *predictive* products.

An important aspect of the data-assimilation procedure is that on time-scales of five-years or so, sustained scientific efforts usually deliver important improvements in the quality of the satellite data (e.g., from improved calibrations and cross-calibrations) in the quality of the algorithms used to interpret the satellite measurements to geophysical quantities, in the quality of the assimilating models, and in the quality of the assimilation algorithms. These developments prompt demands for re-interpretations or reanalyses of the instrumental record using the best available science. Several extended reanalyses covering periods up to 50 years in length have been created to meet such research needs; limited computer resources limit the spatial resolution of these analyses. However, there is also a demand for high-resolution reanalyses of shorter periods; there is likely to be heavy international demand for reanalyses of atmospheric dynamics and composition for the commitment period for the Kyoto protocol (2008-2012).

Operational Dialogues on the Quality of Observations, Models, and Assimilations

For every observation presented to an operational data-assimilation system, the assimilation system can provide an *a priori* estimate of the expected measurement that is totally independent of the actual measurement, as well as an *a posteriori* ‘best estimate’ of what the measurement should have been. Given the millions of satellite measurements available every day, daily or monthly statistics of the differences between actual and expected satellite measurements form a treasure trove for monitoring the performance of the data-assimilation system (including the forecast model), and monitoring the performance of the observing system (Hollingsworth et al., 1986). The statistical material has become the basis of an active dialogue between data users and data producers, which, over the last twenty years, has repeatedly demonstrated its value to all participants. Indeed the benefits for all concerned have been so large that the dialogue has been systematized into a world-wide structure which reports monthly under the aegis of WMO.

Research Dialogues on Scientific Understanding of Remotely Sensed Measurements

A fine example of the value of the dialogue between experts on new instruments, data assimilation methods and *in situ* observations is the discussion of the performance of the forward radiative transfer models used in the AIRS physical retrieval algorithms. Strow et al. (2005) used ground truth from several sensors to assess the uncertainties in the AIRS infrared forward model. Global temperature and humidity fields from operational weather prediction centers were made available to these researchers and to the AIRS science team, in near-real-time. In the early days of the AIRS experiment, rapid comparisons of the differences between the measured and expected radiances (based on the model forecast fields) identified biases in the differences, some of which were attributable to bias in the models and some attributable to errors in the AIRS retrieval algorithms. The instrument issues identified in the initial comparisons with the model data were definitively resolved with field data. As a result of this dialogue between the research teams and the operational teams, within 18 months of launch selected elements of the AIRS radiance data were introduced for operational use in October 2003 and continue to be used for weather forecasting and seasonal forecasting.

PART II: THE DIVERSITY OF METEOROLOGICAL AND OCEANOGRAPHIC OBSERVATIONS

A wide range of atmospheric and ocean data are available and used in current operational practice, and a great deal more data are available for scientific research. Figures C.1 to C.12 show the distribution of routinely available observations available in a 6-hour period centered on 0000 UTC on a randomly chosen date (9 July 2006) from the indicated observing systems.

Figure C.13 shows, for a randomly chosen day, an example of radar altimeter coverage in a 24-hr period from the Jason and Envisat missions. The data are used to measure changes in 'significant wave height' on the ocean surface and surface wind speed.

Figure C.14 shows, for a randomly chosen month, the distribution of Argo floats (yellow). The Argo system provides profiles of ocean temperature and salinity. Also shown are ocean profile measurements from the TOGA-TAO array of moored buoys (red) and ocean profiles (green) from XBT (expendable bathythermograph) measurements made by ships of opportunity.

The diversity, complexity and coverage of the observing systems used in current operational practice are impressive. The improvements in the observing systems over recent decades have contributed substantially to improvements in scientific knowledge, to valuable improvements in forecast capability on short (1-3 day) and medium-range (3-10 days) time scales, and have made possible the creation of new forecast capabilities for variations in the ocean-atmosphere on time scales of months to years such as ENSO (El Niño-Southern Oscillation).

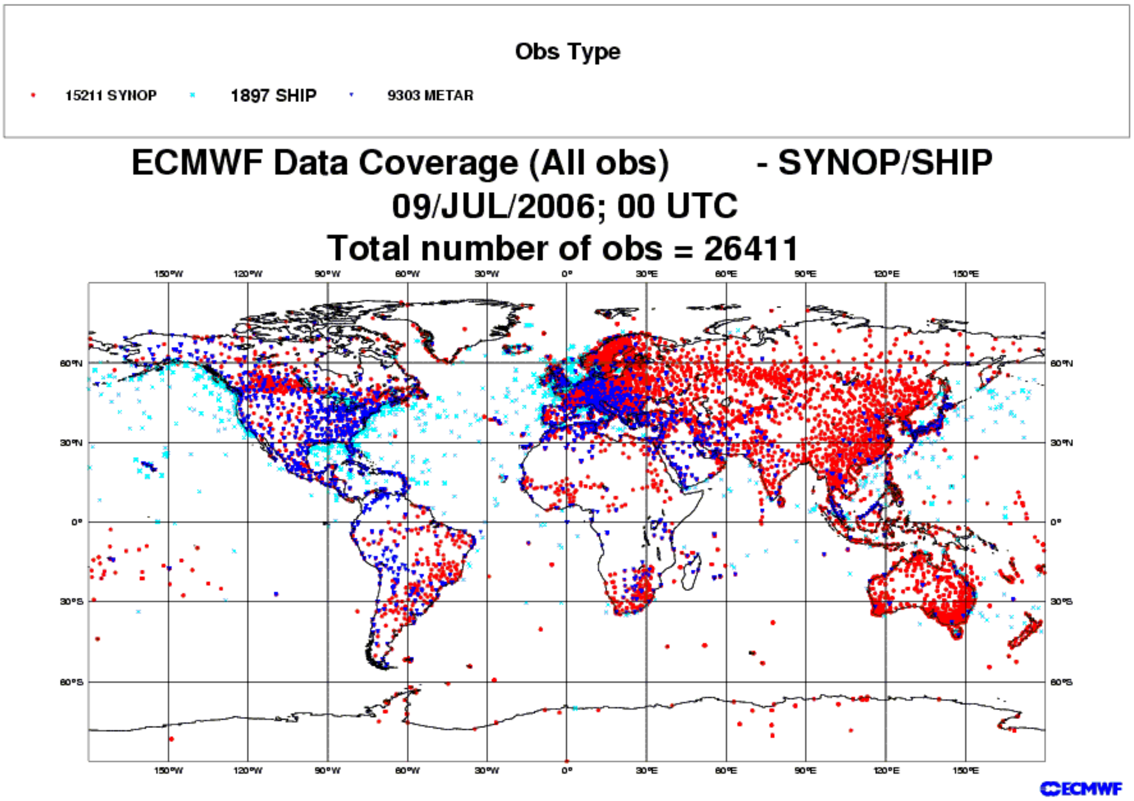


FIGURE C.1 Reports from land stations and ships.

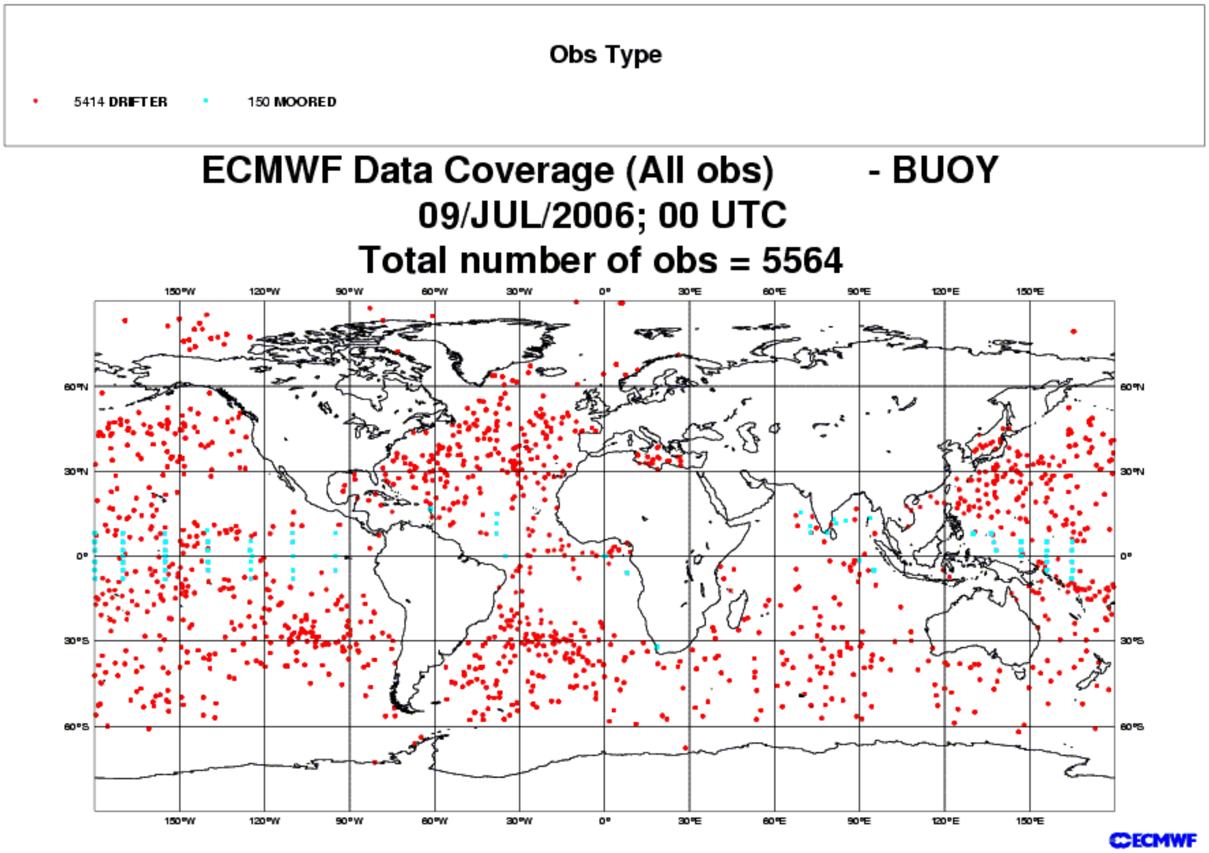


FIGURE C.2 Reports from ocean buoys, including both drifting buoys (red) and moored buoys (blue).

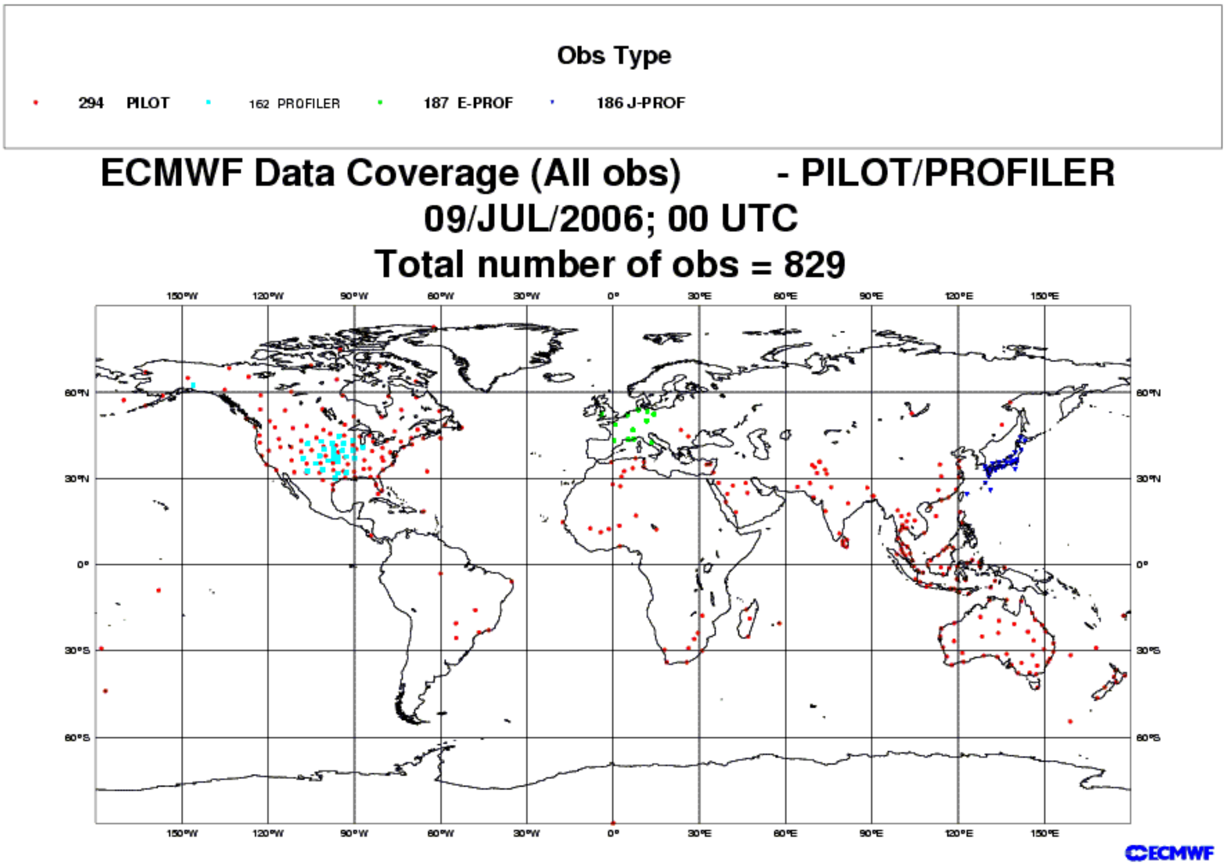


FIGURE C.3 Temperature and humidity measurements from weather balloons.

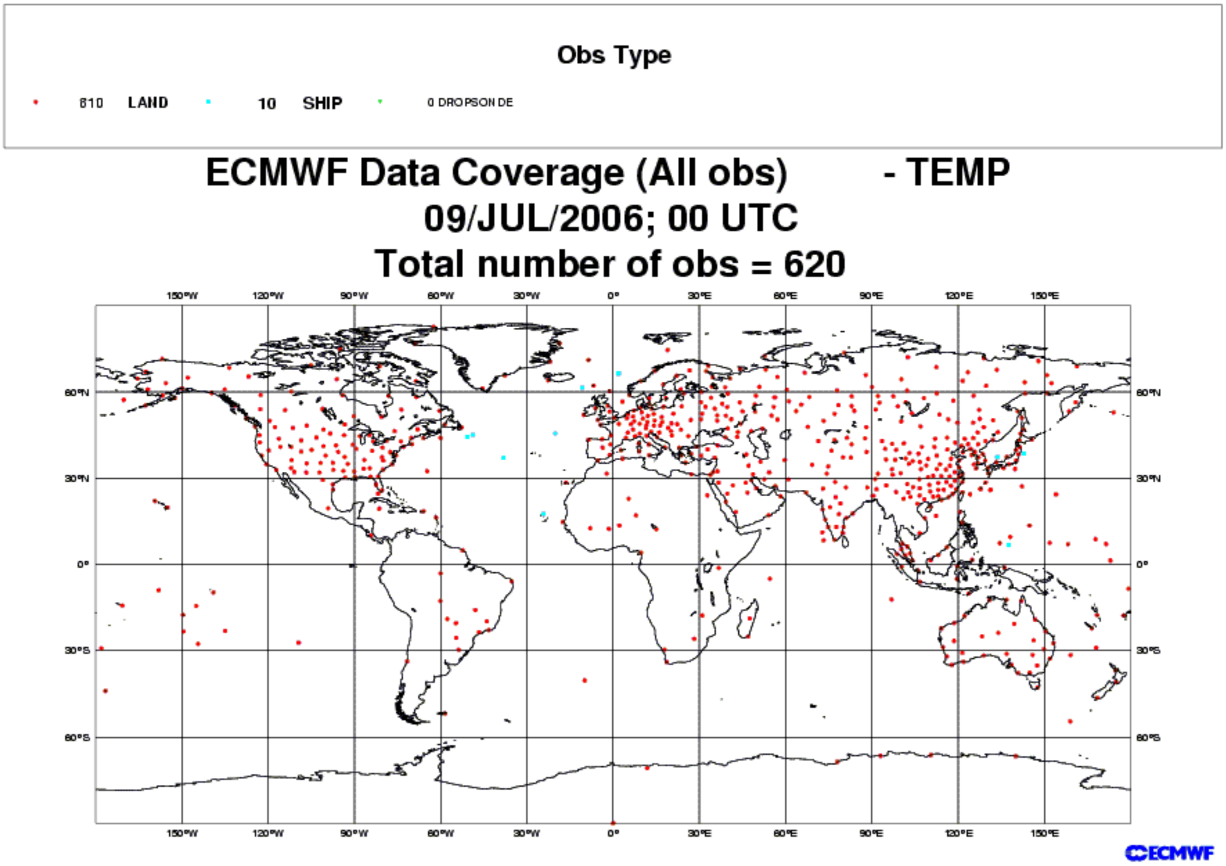


FIGURE C.4 Wind measurements from weather balloons and ground-based microwave profilers (blue, green).

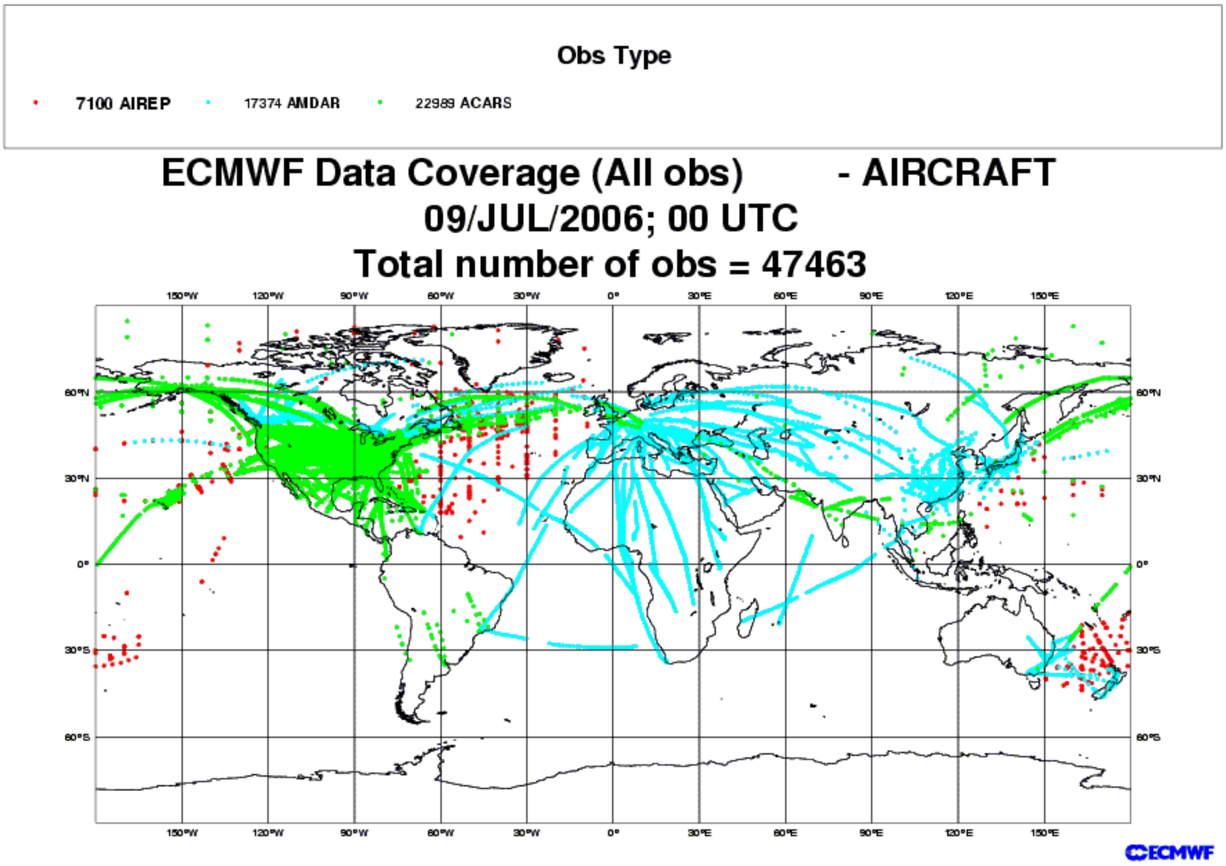


FIGURE C.5 Aircraft reports of wind and temperature.

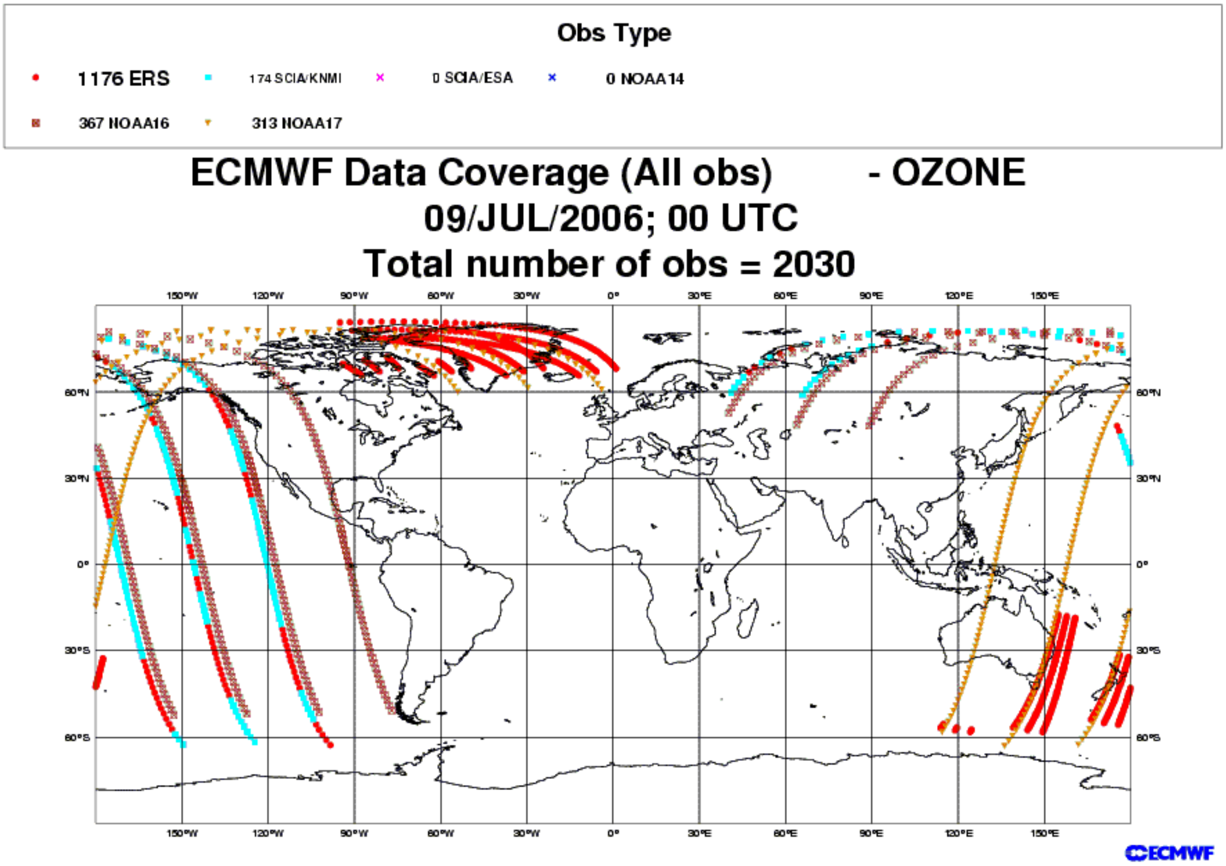


FIGURE C.6 Ozone retrievals using measurements from the U.S. missions NOAA 14/16/17, and from the European ERS-2 and Envisat missions.

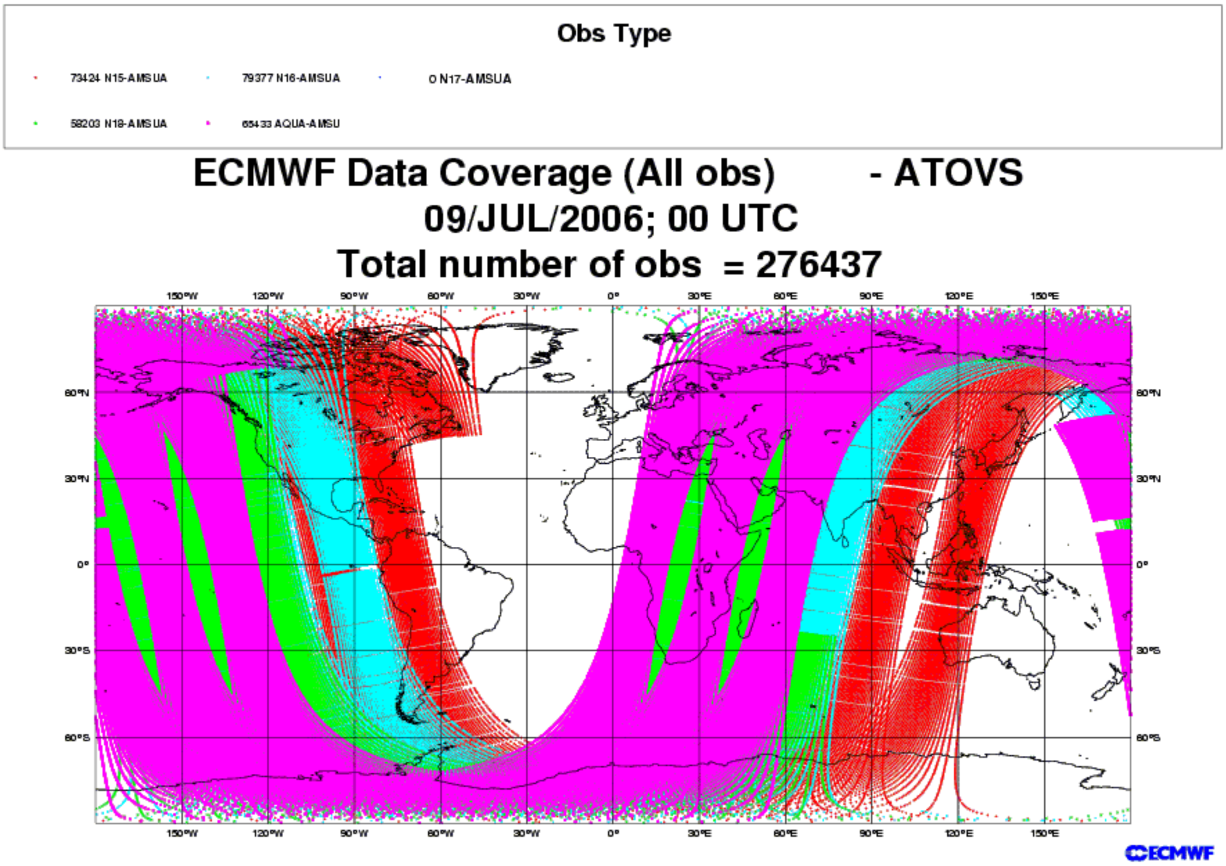


FIGURE C.7 Microwave brightness temperature measurements from the AMSU-A instruments on NOAA 15/16/18 and from the HSB instrument on Aqua.

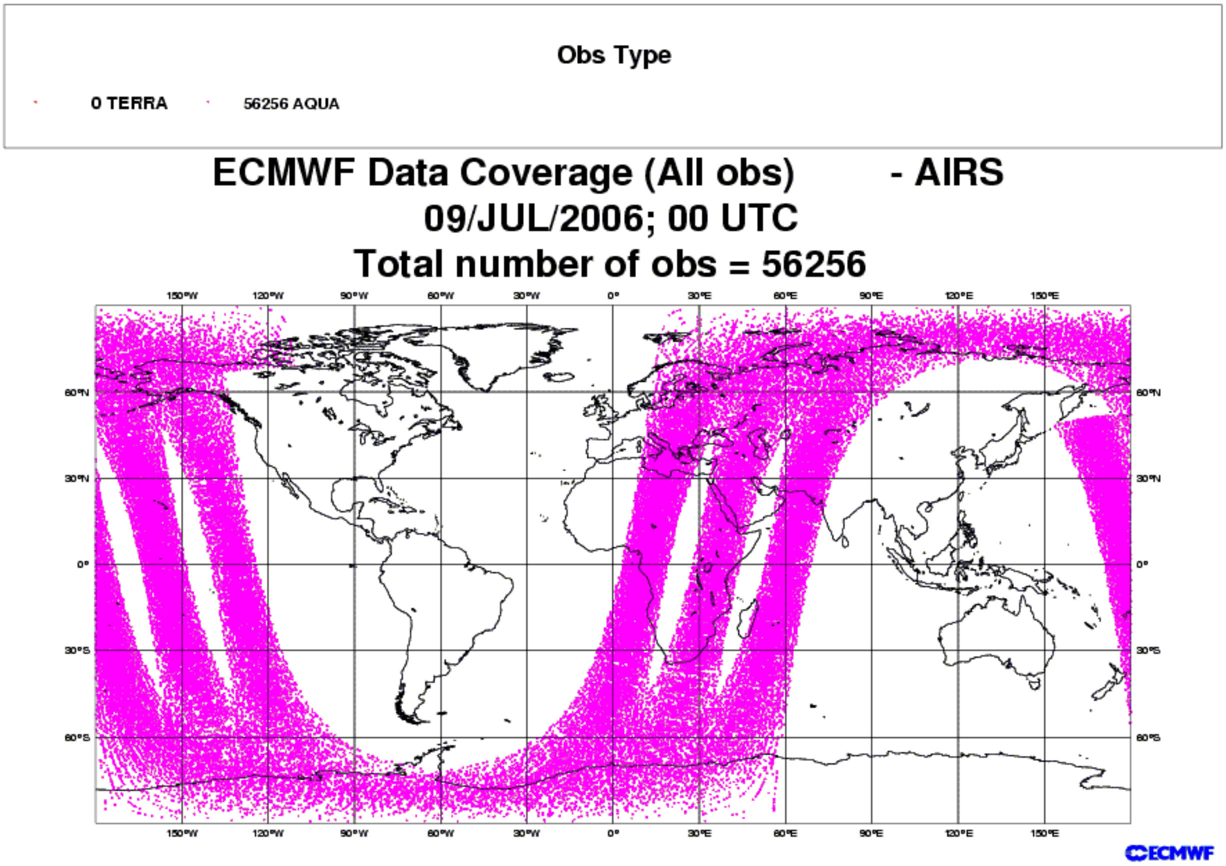


FIGURE C.8 Infrared radiance measurements from the AIRS instrument on NASA's Aqua mission, for estimation of air and sea surface temperature, humidity, ozone, and CO_2.

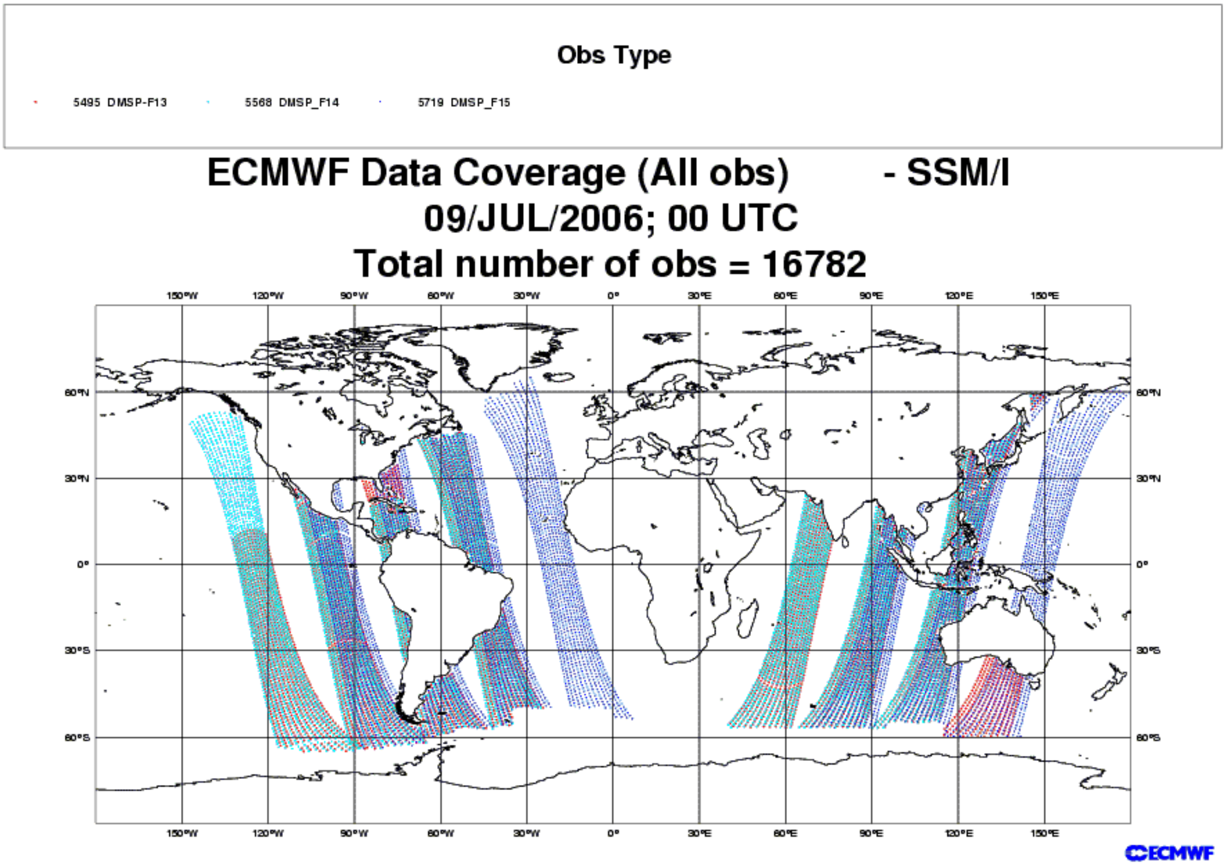


FIGURE C.9 Microwave brightness temperature measurements from the SSM/I instruments on the DMSP series FP-13, FP-14, FP-15, used for estimating, inter alia, total column humidity, ocean surface wind speed, surface rain intensity, and cloud liquid water content.

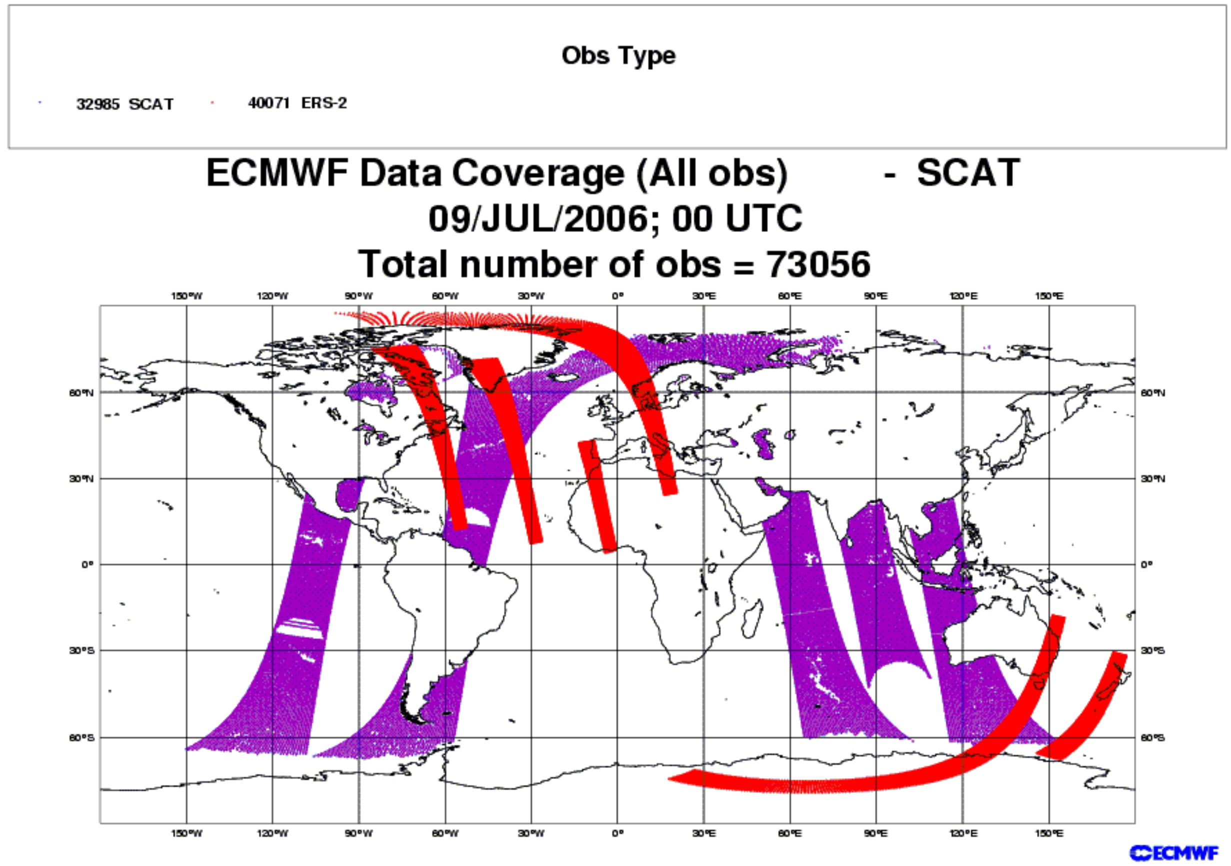


FIGURE C.10 Normalized radar backscatter measurements from the ocean surface made by the QuikSCAT and ERS-2 missions, which are used to infer surface wind speed and direction over the ocean.

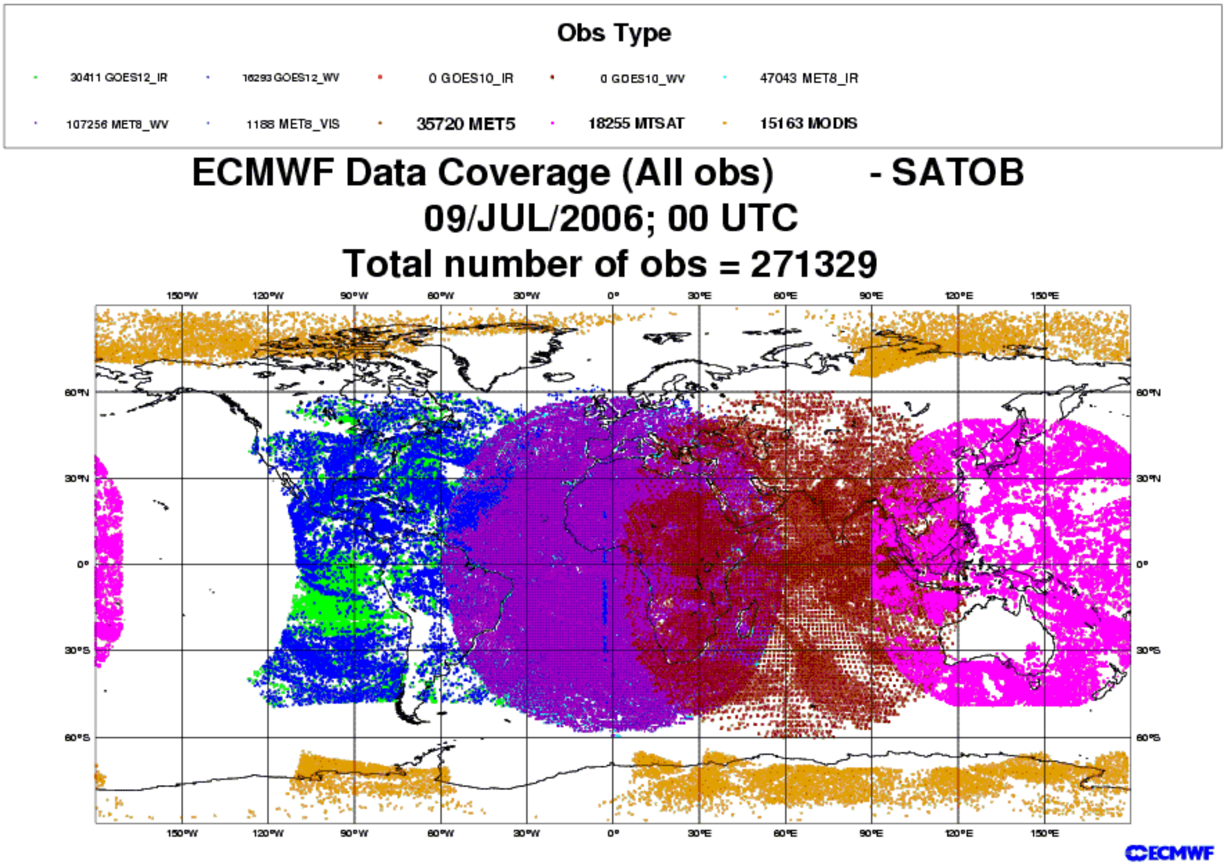


FIGURE C.11 Atmospheric motion vectors estimated (between 50° S and 50° N) from geostationary time-lapse imagery in the infrared window and water vapor bands from the US GOES-12 mission, from the European METEOSAT 5 and 8 missions, and from the Japanese MTSAT mission. In the high polar latitudes, the plot also shows atmospheric motion vectors estimated from time-lapse imagery in the infrared water vapor band from the MODIS instrument on NASA's Terra mission.

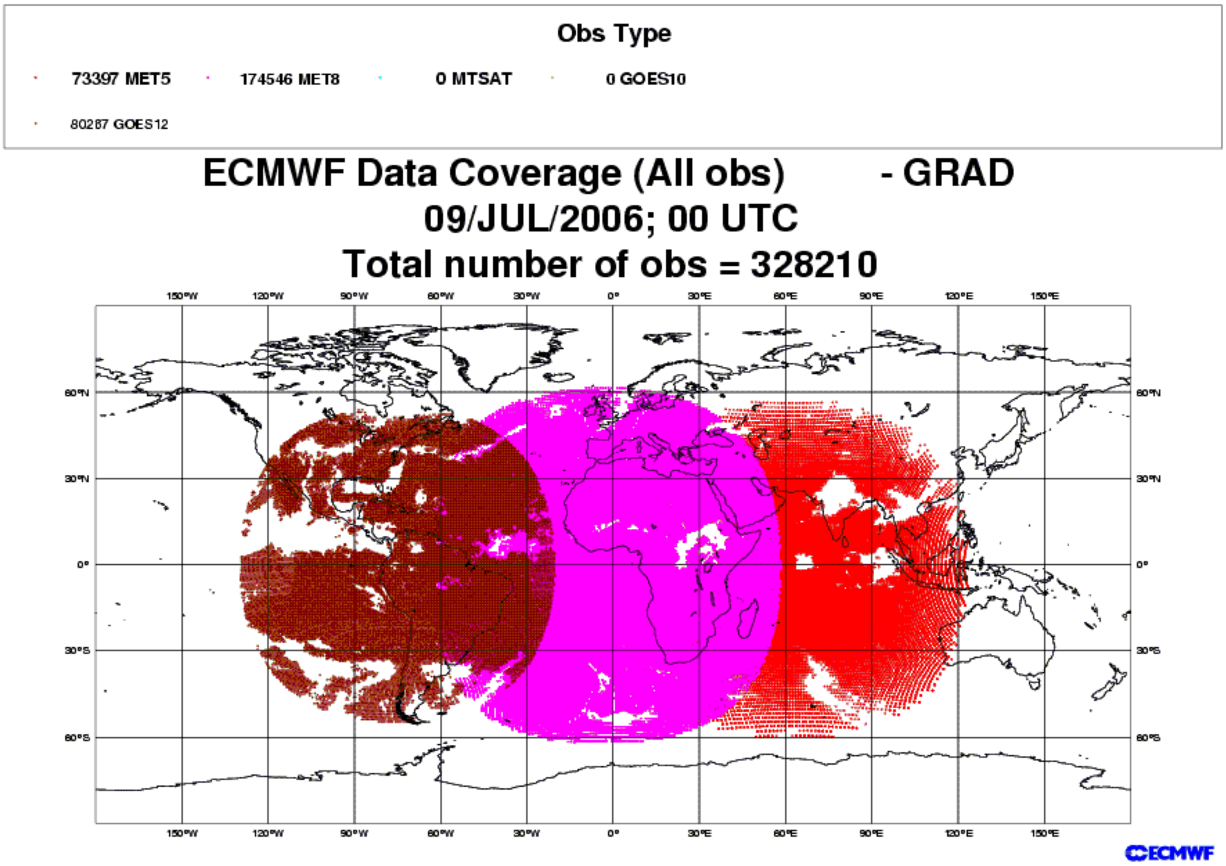
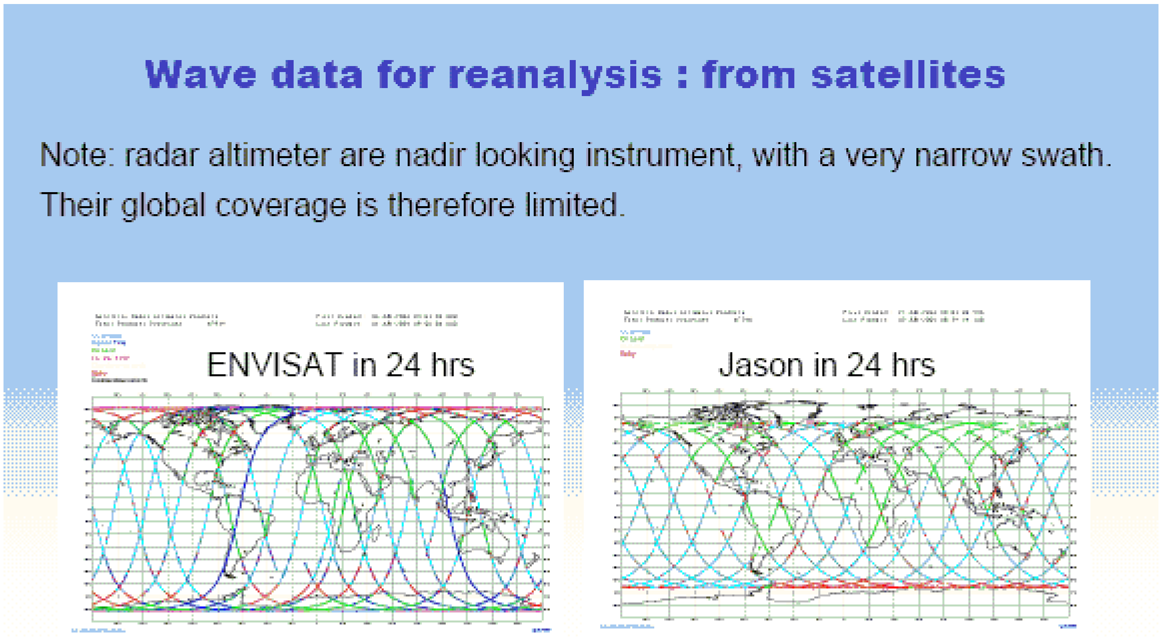


FIGURE C.12 Measurements of atmospheric radiance in the infrared, used for temperature and humidity estimation, from the GOES-12 mission, and from the METEOSAT 5 and 8 missions.



Wave data for reanalysis : from satellites

Note: radar altimeter are nadir looking instrument, with a very narrow swath.
Their global coverage is therefore limited.

ENVISAT in 24 hrs

Jason in 24 hrs

FIGURE C.13 Radar altimeter coverage in 24 hour period from Jason and Envisat missions.

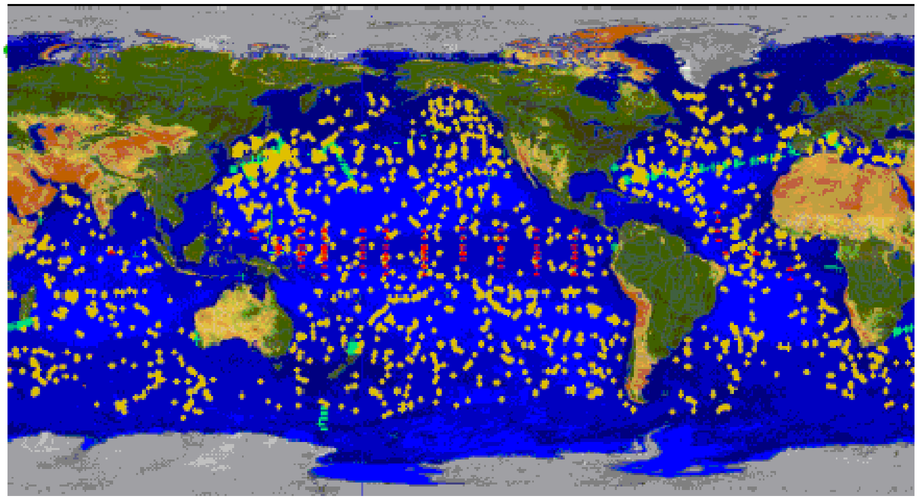


FIGURE C.14. Build up of Argo: Data coverage for February 2005.

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Hollingsworth, A., D. Shaw, P. Lonnberg, L. Illari, K. Arpe, and A. J. Simmons, 1986: Monitoring of observation and analysis quality by a data assimilation system. *Mon. Wea. Rev.*, 114, 861-879.

Strow, L. L.; Hannon, S. E.; De-Souza Machado, S.; Motteler, H. E.; Tobin, D.C. Validation of the Atmospheric Infrared Sounder radiative transfer algorithm. *J. Geophys. Res*., 111(D9): D09S06 10.1029/2005JD006146.

D
Request for Information from Community

To: Members of the Earth and Environmental Science Community
From: Rick Anthes and Berrien Moore
Date: 27 January 2005

As you may know, the Space Studies Board, in consultation with other units of the National Research Council (NRC), has begun a study to generate prioritized recommendations from the Earth and environmental science and applications community regarding a systems approach to the space-based and ancillary observations that encompasses the research programs of NASA and the related operational programs of NOAA. The study will also consider such cross-agency issues such as the development of an operational capability for land remote sensing.

The study, which will be carried out over a two-year period and organized in a manner similar to other NRC "decadal surveys," seeks to establish plans and priorities within the sub-disciplines of the Earth sciences as well as an integrated vision and plan for the Earth sciences as a whole. It will also consider Earth observations requirements for research and for a range of applications with direct links to societal objectives. We have been appointed by the NRC as study co-chairs.

An open web site <http://qp.nas.edu/decadalsurvey> has been created to describe the study and to provide an opportunity for community input throughout the study process. In addition, a number of outreach activities are planned, including community forums in conjunction with the fall 2004 and 2005 AGU meetings and the January 2005 and 2006 meetings of the American Meteorological Society.

In order to obtain the greatest possible input of ideas from the community about potential mission concepts addressing Earth Science research and applications, we are soliciting input from the broad community. We are especially seeking ideas for missions or programs that are directly linked to societal needs and benefits.

The ideas and concepts received will be reviewed by one or more of the Survey's seven study panels, which are addressing the following themes:

1. Earth Science Applications and Societal Needs
2. Land-use Change, Ecosystem Dynamics, and Biodiversity
3. Weather (including chemical weather and space weather)
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

Based on their potential to contribute to research and/or applications and societal needs, each panel may select one or more of the concepts for further technical and cost assessments. The Panels will recommend, in priority order, a number of proposed missions for carrying out over the period 2005-2015, taking into account a set of established criteria as described below. The Executive Committee of the Decadal Study will interleave the Panel Recommendations, to produce a final set of recommended missions, in priority order.

Three categories of missions are solicited, following the approximate total (over lifetime of mission) cost guidelines:

1. Small missions that cost less than $200 M.
2. Medium-size missions that cost between $200 M and $500 M.
3. Large missions that cost more than $500 M.

Each of the proposed missions may contribute to research or operations, or both. Note: Mission costs refer to costs that would be incurred by NASA in current (FY05) dollars.

We invite you to write a concept paper for a new space-based mission or measurement, from existing or new vantage points, that promises to advance an existing or new scientific objective, contribute to fundamental understanding of the Earth system, and/or facilitate the connection between Earth observations and societal needs. We anticipate concepts that will range from free-flying spacecraft to instruments that might be included in follow-ons or as additions to the NPOESS and GOES series of spacecraft. Constellations of spacecraft or spacecraft that fly in formation with existing, planned, or future satellites may also be considered.

All responses will be considered non-proprietary public information for distribution with attribution. The concept papers should be no longer than ten pages in length and provide the following information, if possible: [Additional information added 4/12/05: 10-page limit is a rough guideline, not absolute limit, and refers to single-space text excluding references and front matter]

1. A summary of the mission concept, including the observational variable(s) to be measured, the characteristics of the measurement if known (accuracy, horizontal, vertical and temporal resolution), and domain of the Earth system (e.g. troposphere, upper-ocean, land surface).
2. A description of how the proposed mission will help advance Earth science and/or applications, or provide a needed operational capability, for the next decade and beyond.
3. A rough estimate of the total cost (large, medium, or small as defined above) of the proposed mission over ten years. For operational missions the costs should include one-time costs associated with building the instrument and launch and ongoing operational costs.
4. A description of how the proposed mission meets one or more of the following criteria, which will be used to evaluate and prioritize the candidate proposals:
    a. Identified as a high priority or requirement in previous studies, for example NRC and WMO reports and existing planning efforts such as the International Working Group on Earth Observations (IWGEO: http://iwgeo.ssc.nasa.gov);
    b. Makes a significant contribution to more than one of the seven Panel themes;
    c. Contributes to important scientific questions facing Earth sciences today (scientific merit, discovery, exploration);
    d. Contributes to applications and/or policy making (operations, applications, societal benefits);
    e. Contributes to long-term monitoring of the Earth;
    f. Complements other observational systems;
    g. Affordable (cost-benefit);
    h. Degree of readiness (technical, resources, people);
    i. Risk mitigation and strategic redundancy (backup of other critical systems);
    j. Fits with other national and international plans and activities.

Describe each proposed mission in terms of its contributions to science and applications, how the mission meets the above prioritization criteria, its benefits to society, technical aspects, schedule and rough estimate of costs. The description should provide enough detail that the potential value and feasibility of the mission can be evaluated by an independent group of experts.

For full consideration, please submit the concept paper by May 16, 2005 via e-mail to: rfi@nas.edu . Questions about the RFI may be directed to the study director, Art Charo (acharo@nas.edu), or to us: (anthes@ucar.edu); (b.moore@unh.edu). You can also contact Dr. Charo by telephone at 202 334-3477, or by fax at 202 334-3701.

E
List of Responses to Request for Information

RFI	Title	Brief Description of Objective
1	ACCURATE: Atmospheric Climate and Chemistry in the UTLS Region And climate Trends Explorer	To advance understanding of climate processes and atmospheric physics and chemistry in the UTLS region, monitor climate variability and change, and provide climate model validation and improvement via combined radio and IR laser-crosslink occulation
2	Submillimeter Infrared Radiometer Ice Cloud Experiment	To provide spatially-resolved daily global measurements of upper tropospheric ice water path and ice crystal size via submillimeter IR radiometry
3	Combined Active and Passive Environmental Sounder (CAPES) Mission for Water Vapor, Temperature, Aerosol and Cloud Profiling From Space	To provide high vertical resolution measurements of water vapor, aerosols, and clouds along the satellite ground track, and full three-dimensional (3D) water vapor and temperature coverage at a lower vertical resolution cross-track via a differential absorption lidar and fourier transform spectrometer
4	Active Mission for Global CO2 Measurements	To significantly expand the set of global atmospheric CO_2 observations via an active laser instrument for column measurements of CO_2 down to the surface or cloud tops and pulsed aerosol and cloud lidar to determine surface elevation and aerosol and cloud distributions along lidar line of sight
5	Active Temperature, Ozone and Moisture Microwave Spectrometer	To provide long-term characterization of state of Earth's troposphere and middle atmosphere via cm- and mm-wavelength satellite-to-satellite occultation measurements
6	Adaptive Atmospheric Sounding Mission	To sound the atmosphere via long-life networked stratospheric balloon platforms instrumented with remote sensing and *in situ* instruments
7	Aerosol Global Interactions Satellite	To measure the three-dimensional distribution of aerosol abundances, sizes, shapes, and absorption, and determine aerosol impacts on climate and air quality via multiangle spectropolarimetric imager and high spectral resolution lidar
8	Moderate Resolution Infrared Imaging Spectrometer (MIRIS)	To improve studies of small scale meteorological and climatologic forcing and improve accuracy of measurements of minor gas species via high spatial and spectral resolution IR imager
9	Atmospheric Remote-Sensing and Imaging Emission Spectrometer	To measure upper atmospheric water vapor with unprecedented accuracy, while providing temperature profiles, surface emissivity, ozone, CH_4, CO, CO_2, SO_2, aerosols, cloud top height, and cloud temperature via observation of the IR spectrum with high resolving power

RFI	Title	Brief Description of Objective
10	The National Global Operational Environmental Satellite System (NGOESS): Designed to Fulfill NOAA's Future Satellite System Requirements and those of the GEOSS	To observe key climate and environmental parameters post-GOES-R and NPOESS via a constellation instrumented with an ultra-spectral imager/sounder and synthetic thinned aperture microwave pushbroom radiometer/sounder.
11	Cellular Interferometer for Continuous Earth Remote Observation: A Concept for Radio Holography of the Earth	To provide continuous, high-resolution global imaging, surveillance, and remote sensing both actively and passively at radio frequencies via a constellation of 1000+ radio satellites
12	The Geohazards IGOS Theme: Space Component Requirements, An analysis for discussion at CEOS SIT-13	To describe IGOS Geohazard Theme's five specific priority requirements for space observations
13	Cloud Height and Altitude-Resolved Motion Stereo-imager (CHARMS)	To provide measurements of cloud-top height and cloud-motion vectors by a multi-angle stereo technique that is uniquely relevant to long-term climate data records
14	Cloud Hydrology and Albedo Synthesis Mission	To measure water content of clouds concurrently with albedo and cloud-top height via multi-angle imager and dual angle passive microwave instrument, extending application to land/ocean day/night
15	E-mail Comment on Operational Oceanography	To emphasize importance of addressing satellite remote sensing needs of operational oceanography
16	The Climate Benchmark Constellation: A Critical Category of Small Satellite Observations	To provide absolute infrared spectrally resolved radiance, GPS radio occultation and millimeter-wave absorptive radio occultation, solar irradiance and absolute shortwave flux reflected to space, and enable absolute climate records in perpetuity via on-orbit standards with International System of Units traceability
17	Climate Scope Mission Concept Paper	To assemble assimilated data sets via an R&D program, validation and verification program, integration and production program, and the necessary computing, data management and dissemination infrastructure
18	Climate Calibration Observatory: NIST in Orbit	To calibrate radiometers, spectrometers, and interferometers in orbit
19	Cold Land Processes Pathfinder Mission Concept	To measure fresh water stored in snow on land and on ice sheets, enabling a major leap-ahead in understanding snow process dynamics in the global water cycle and to forge a pathway to operations, initiating significantly enhanced global monitoring and prediction of snow properties for multiple water, weather, and climate applications.
20	Orbital Laser Sounder Mission for Global CO2 Measurements	To measure global distribution of CO_2 mixing ratio in the lower troposphere, day and night, and generate the first monthly global maps of the lower tropospheric CO_2 column abundance to help understand the global carbon cycle and global climate change via active laser sounding

RFI	Title	Brief Description of Objective
21	Coastal Ocean Carbon Observations and Applications	To quantify the pools and fluxes of carbon in the coastal ocean, knowledge of which is essential for understanding the role of the global carbon cycle in climate variability and change, via high resolution hyperspectral imagery
22	Email Comment: Landsat 5	To urge the removal of downlink fees for Landsat 5 data
23	Continuous Coastal Awareness Network (C-CAN): A Response to the NRC Decadal Study Request for Information	To detect, predict, and manage change for sustainable development in heavily populated coastal regions via a sensorweb system approach involving multi-sensor satellite observations of sea surface height, coastal currents and winds, and sea spectral reflectance from different Earth vantage points coupled with *in situ* observations for coastal event detection
24	Crustal Magnetic Field Measurement Missions	To provide systematic global magnetic field observations needed to distinguish magnetic field variations over various spatial and temporal scales, and to separate the effects of the components of the magnetic field via stratospheric balloon platforms
25	Daedalus: Earth-Sun Observations from L1	To characterize the direct influence of solar variability on Earth system via simultaneous observation of key solar emission/space weather parameters and spectrally resolved radiances over the entire illuminated Earth from an L1 vantage point
26	The Need for New Geodetic Satellites for Observing Long-Term, Long-Wavelength Gravity Variations and Improved Terrestrial Reference Frame Determination	To improve the determination of changes in the Earth's gravity field, determination of the terrestrial reference frame, and the separation of tidal signals in space geodetic measurements via passive, laser retro-reflecting geodetic satellites
27	Water and Ocean Wind Sensor	To enhance characterization, understanding, and prediction of persistent small-scale ocean-atmosphere coupling, tropical cyclones, and coastal processes by continuing the contiguous wide-swath measurement of ocean surface vector wind via a single instrument combining active and passive microwave techniques
28	Improved Weather Prediction, Climate Understanding, and Weather Hazard Mitigation through Global Profiling of Horizontal Winds with a Pulsed Doppler Lidar System	To demonstrate a new capability that would meet the science and operational communities' needs for global profiles of horizontal wind velocity via pulsed Doppler lidar
29	Providing Global Wind Profiles: The Missing Link in Today's Observing System	To accurately measure the 3-D global wind field via multiple Doppler lidars
30	Earth Sciences from the Astonomer's Perspective: A Deep Space Climate Observatory	To observe the Earth in a bulk thermodynamic sense, as an open system exchanging radiative energy with the Sun and space via continuous observation from an L1 orbit
31	Earth Sciences Applications in Human Health	To advocate greater emphasis on environmental causes for disease emergence and environmental monitoring of pathogens and vectors, involving disciplines beyond those of traditional biomedical science

RFI	Title	Brief Description of Objective
32	The Ecology of Global Infectious Disease: A Research Program	To establish a research program using geoscience in combination with epidemiology to improve use of satellite data in epidemiological applications and develop requirements for a spacebased platform
33	Air Pollution Investigation Constellation	To quantify sub-regional emissions of precursors of smog and particulate matter, and the effects of transformation processes over long ranges on air quality, enabling accurate prediction and control of global air pollution via a constellation approach consisting of a MEO/GEO platform with a UV/VIS/NIR spectrometer and thermal emission IR spectrometer and a LEO platform with multiangle spectropolarimetric imager and IR solar occultation instrument
34	Monitoring Climate Change by Solar Occultation	To monitor climate change via HALOE-type solar occultation instruments
35	Geostationary Advanced Imager for New Science	To observe the diurnal cycle of the Earth's surface temperature with 1 km resolution from GEO
36	Student Reflective GPS Experiment	To provide space-based measurements of GPS reflections to determine the utility of measuring Earth surface parameters such as ocean wind speed/direction, sea surface height, and land surface soil moisture
37	Global Environmental Micro Sensors (GEMS): A New Instrument Paradigm for In situ Earth Observation	To make ultra-high spatial and temporal resolution environmental measurements over an immensely broad range of atmospheric conditions to provide calibration/ground truth for space-based remote sensing systems, expand our understanding of the Earth system, and improve weather forecast accuracy and efficiency well beyond current capability via *in situ* airborne buoyant probes
38	The Flora Mission for Ecosystem Composition, Disturbance and Productivity	To measure fractional cover of biological materials, canopy water content, vegetation pigments and light-use efficiency, plant functional types, fire fuel load and fuel moisture content, and disturbance occurrence, type, and intensity to advance global studies and models of ecosystem dynamics and change
39	GEM	To improve severe weather forecasting by profiling temperature and moisture fields via combined microwave imager and a sounding radiometer
40	Geodetic Analysis Reference Network: GARNET Program	To develop and sustain the fundamental reference frame to meet NASA's, NOAA's, and the broader community's needs over the next decade via a program for managing the high precision networks, analysis techniques and integrated data systems of the Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR), extending to gravity observation networks.
41	The GeoSTAR GEO Microwave Sounder Mission: The Geostationary Synthetic Thinned Array Radiometer	To take temperature and humidity profiles, with emphasis on storms and tropical cyclones and to contribute important measurements to research related to the hydrologic cycle via a geostationary dual-array system for microwave sounding measurements

RFI	Title	Brief Description of Objective
42	GRACE follow-on	To contribute to continuous, multi-decadal monitoring of the temporal variations of Earth's gravity field via a GRACE follow-on
43	GNSS Geospace Constellation	To contribute to Sun-Earth connection science using transmissions of global navigation satellite systems to measure total electron content, giving information about ionosphere and plasmasphere dynamics via at least 6 LEO spacecraft with advanced GPS receivers tracking existing and anticipated Global Navigation Satellite System signals
44	Glaciers and Ice Sheets Mapping Orbiter	To measure the surface and basal topography of terrestrial ice sheets and determine the physical properties of glacier beds via radar
45	Global Aerosol Monitoring Mission	To globally monitor the scattering and absorption properties of aerosol particles
46	Global Water Resources Mission	To provide a 20-year international plan for enabling society to assess and predict the global availability of fresh water under the influence of weather and climate variability via an international effort consisting of about two dozen satellite systems, each of which is comparable with current operational GEO and LEO satellites
47	GLORY	To monitor factors influencing radiative balance between Earth and space to improve ability to understand and predict climate change via aerosol and irradiance measurements by a total solar irradiance sensor
48	Geostationary Observatory for Microwave Atmospheric Sounding	To provide a system for humidity and temperature sounding and frequent precipitation observation from geostationary orbit via sub-mm and mm-wave radiometry
49	A Constellation for High Resolution Sea Surface Topography with Frequent Temporal Revisit	To provide continuous coverage oceanography for mesoscale process characterization and tsunami warning via a constellation of six satellites in low Earth orbit
50	Proposition to Observe H2S Emitting from Ocean Surface	To observe H_2S emitting from the ocean surface and provide high-resolution ocean color
51	Decadal Survey Proposal	To advocate measurement of the heat flux of the mantle of Earth in order to better understand how the systems of Earth work and interconnect
52	Exploration of the Earth-Sun System from L1	To provide global mapping of atmospheric composition every 30-60 minutes from an L1 vantage point, enabling understanding of the relationship between solar activity and structure and dynamics of Earth's atmosphere
53	Concept Paper Submitted to the Decadal Study Request for Information issued by the National Research Council	To encourage the Earth and environmental sciences communities to consider the importance of the "human factor" in usage and interpretation of data and advocate collaboration with cognitive systems engineers to create demonstrably useful and usable human-centered technologies

RFI	Title	Brief Description of Objective
54	An Autonomous Aerial Observing System for the Exploration of the Dynamics of Hurricanes	To improve our scientific understanding of tropical cyclone genesis and intensity change processes by providing the first continuous high-resolution observations of the thermodynamic and kinematic evolution of the inner core of a tropical cyclone from genesis to dissipation or landfall via long-endurance UAV platform
55	Detecting Human-Induced Land Degradation Impact on Semi-Arid Tropical Rainfall Variability Based on Measurements from Satellite Products	To obtain an improved understanding of the variation of spatial signature on land degradation in semi-arid tropical regions and how human induced land cover changes can have a direct effect on precipitation in these regions via analysis of existing satellite vegetation and precipitation data sets at various spatial and temporal scales
56	Global Hydrosphere Mapper	To provide high-resolution measurements of the surface of the ocean and water bodies on land via radar interferometry
57	Biomass Monitoring Mission Lidar Instrument	To measure the amount of carbon stored in Earth's above-ground biomass and gain a better understanding of forest ecosystem function in the global carbon cycle via lidar
58	Importance of Outreach and Education	To emphasize the importance of outreach and education in communicating science information and new research
59	Infrared Thermal Imaging of the Earth's Surface	To routinely measure the thermal energy of the surface of the North American continent and correlate with population distribution and urban centers
60	Observations of Tropospheric Air Chemistry Processes from a Geostationary Perspective	To understand roles of tropospheric ozone and aerosols in perturbing the Earth system and understand their effects on the global atmosphere and air quality from GEO
61	Composition of the Atmosphere from Mid-Earth Orbit	To fill gaps in observations of upper troposphere processes, while providing a new capability for determining the role of fast processes in linking regional pollution, global air quality, and climate change via measurement of chemical species, ice cloud parameters, temperature, lower troposphere O_3, NO_2, SO_2, CO, H_2CO, CH_4, BrO, aerosol/cloud properties, and surface UV-B flux using a microwave sounder and imager in MEO orbit
62	Operational Ocean and Land Mission	To gather data that can be used in croyspheric, land, land deformation, ecology, atmospheric, and hydrologic applications via synthetic aperture radar, spectometry, and altimetry
63	A Solar Occultation Mission to Quantify Long-Term Ozone and Aerosol Variability	To produce high vertical resolution profiles of ozone and aerosols from the upper troposphere through the stratosphere, provide a long-term (10 year) ozone and aerosol data set, and corroborate the performance of new instruments via solar occultation
64	Pulsed LF-HF-VHF Radio Emission Possibly Associated with the Burakin Seismic Activity in Western Australia	To report a new kind of radio emission possibly related with seismic activity
65	E-mail Comment	To advocate consideration of science-policy interfaces and provide background on the relationships between Earth system science and policies

RFI	Title	Brief Description of Objective
66	The CLAIM 3-D Mission	To advance understanding of aerosols and cloud and precipitation development via multi-angle, polarized spectral imaging, and a cloud rainbow camera
67	Monitoring Atmosphere Turbulence and Humidity	To measure temperature and water vapor profiles, tropospheric turbulence, and cloud and aerosol properties via differential absorption lidar
68	Long-Term Measurement Assurance Program for Climate-Change Satellite Systems	To provide a measurement assurance system at least as rigorous as international metrology institutes to ensure accurate climate measurements
69	A Constellation of Mixed-Orbit Micro-Satellites for Monitoring Global Land Change and Ecosystem Dynamics	To acquire high-resolution data to document land use/cover change and ecosystem dynamics via a constellation of microsatellites in various orbits
70	Microwave Observatory of Subcanopy and Subsurface	To provide measurements for estimation of global soil moisture under substatial vegetation canopies and at useful soil depths via multi-frequency synthetic aperture radar
71	GEOCarb Explorer: A Geosynchronous Hyperspectral Mission Providing Continental-Scale Carbon Cycle Ecosystem Observations	To advance scientific understanding of carbon cycle dynamical interactions between the Earth's biota and the atmosphere via observation from GEO
72	Multiplatform Interferometric SAR for Forest Structure and Subcanopy Topography and Soil Moisture	To measure 3D forest structure, topography, and soil moisture underlying forest canopies using a multiplatform InSAR system
73	Biomass Monitoring Mission	To make global measurements of above-ground woody biomass carbon stock, forest 3-D structure, and to monitor changes in terrestrial carbon pool as a result of disturbance and recovery processes via lidar and radar
74	Suborbital Earth System Surveillance	To develop an environmental surveillance program filling observation gaps between satellite and aircraft observation capabilities via High Altitude Long Endurance (HALE) UAVs
75	Nightsat	To measure the spatial distribution and brightness of nocturnal lighting worldwide at a spatial resolution that permits the delineation of key features found in human settlements via observation in the vis/NIR and thermal bands
76	The Far-Infrared Spectrum: Exploring a New Frontier in the Remote Sensing of Earth's Climate	To improve understanding of the natural greenhouse effect, atmospheric cooling by water vapor, and the role of cirrus clouds in climate via direct measurements of the far-infrared portion of the Earth's emission spectrum
77	Low-Earth-Orbit Global Mapping of Boundary Layer Carbon Monoxide	To measure global boundary layer CO via polarization-modulated gas filter correlation radiometry
78	Space-based Doppler Winds LIDAR: A Vital National Need	To provide high-resolution global tropospheric wind observation in support of improved long-range weather forecasting and other societal applications via Doppler wind lidar

RFI	Title	Brief Description of Objective
79	Need for Integrated Water Cycle Observations from Space	To provide comments and background information on numerous water cycle observations and outline key considerations for developing a future water cycle observation strategy
80	A Low-Cost Multispectral Earth Observing System	To enhance Landsat and OLI data and satisfy requirements currently unfilled by a single Landsat-type satellite via a constellation multispectral Earth observing system with four satellites
81	A Space Mission to Observe Phytoplankton and Assess its Role in the Oceanic Carbon Cycle	To provide daily global measurements of ocean color and aerosols to help to quantify ocean's role in uptaking atmospheric CO_2, via natural fluorescence and Raman scattering observations
82	Surface Shortwave and Longwave Broadband Network Observation Uncertainty for Climate Change Research, Verification is Needed	To provide climate quality surface downwelling LW and SW broadband irradiance on a global scale via improved cross-network calibration, instrument standardization, long-term instrument intercomparisons, and development of new instruments and sensors
83	InSAR Applications for Exploration of the Earth	To precisely map Earth surface change and deformation due to tectonic, volcanic, and glacial processes with sub-cm accuracy via space-borne radar interferometry
84	Solar Occultation Instruments for Measurements of Ozone Trends	To monitor global ozone trends, aerosols, water vapor, and NO_2, and provide calibration of OMPS stability via solar occultation observations
85	Data Assimilation and Objectively Optimized Earth Observation	To describe a vision for a future objectively optimized Earth observation system with integrated scientific analysis via a dynamically-adapting system
86	Ocean Carbon, Ecosystem and Near-Shore Mission Concept	To achieve the most accurate and spectrally-broad global measurements of ocean water-leaving radiances ever conducted via a single spectrometer, and to utilize these data to effectively separate the wide variety of optically active in-water constituents
87	Ocean and Land Operational Mission of the U.S.	To gather data that can be used in croyspheric, land, land deformation, ecology, atmospheric, and hydrologic applications via synthetic aperture radar, spectometry, and altimetry
88	'Our Vital Skies': A preliminary concept of a coordinated research program for the coming decade	To substantially improve understanding of the influence of cloud-aerosol-precipitation interactions on regional and global weather and climate via a program focusing on the microphysical linkages between aerosols, clouds, and the hydrological cycle.
89	Multispectral Land Sensing: Where From, Where to?	To assess the long-term potential of technology for land remote sensing and discuss needed development of a hyperspectral data analysis system
90	Polar Environmental Monitoring, Communications, and Space Weather from Pole Sitter Orbit	To provide continuous environmental and meteorological monitoring of polar regions, a unique perspective on space weather monitoring of Sun-Earth system, and constant communication links between deep polar regions and the rest of the world
91	A radar altimeter for bathymetry, geodesy, and mesoscale oceanography	To provide a global map of deep ocean bathymetry and gravity field at a resolution of 6-9 km using delay-Doppler radar altimetry to measure sea-surface slope

RFI	**Title**	**Brief Description of Objective**
92	Contributions of Radio Occultation Observations to the Integrated Earth Observation System	To resolve temperature and water vapor of the global atmosphere with unprecedented accuracy and resolution sufficient to meet requirements of weather and climate forecasting and climate monitoring via an operational system of radio occultation observations
93	Advanced Limb Imaging Sounder Experiment Mission	To measure the distribution of upper troposphere and lower stratosphere temperature, water vapor, ozone, clouds, and aerosols at high vertical and improved horizontal resolution in order to understand the role of the upper troposphere and lower stratosphere region in the radiative forcing of climate and climate-chemistry feedback
94	Molniya Orbit Imager	To extend GOES-type imagery to high-latitudes via an imager in Molniya orbit
95	Robust IR Remote Sensing for Carbon Monoxide, Methane, and Ozone Profiles	To make daily measurements of the vertical structure of trace gases including CO, methane, and ozone
96	GRACE follow-on	To provide global measurements of terrestrial water, ice, and ocean mass variations via measurement of temporal variations in Earth's gravitational field
97	Spaceborne Advanced Visible Infrared Imager Concept	To produce high-resolution maps of reflected and emitted radiance of surface every 8 days via thermal IR imagery
98	Mission of Scatterometer and Along-Track Interferometer for Ocean Current and Vector Wind Applications	To acquire high-resolution measurements of both ocean surface current and vector wind as a significant improvement over current measurements via scatterometry and along-track interferometry
99	Sensing of H2O in the Upper Troposphere	To simultaneously measure vertical profiles of H_2O and HDO in the tropics and subtropics through the upper troposphere and lower stratosphere via IR solar occultation in order to constrain the dominant mechanisms regulating the abundance of water in critical regions of the Earth's atmosphere
100	Draft GPM Overview Document	To provide near-global measurements of rainfall, 3-D cloud structure, and precipitation using a microwave imager and a dual-frequency precipitation radar
101	Stratospheric Earth Radiation Balance (SERB) Missions using Balloons	To investigate stratospheric Earth radiation balance via long-life stratospheric balloons
102	Structure and Inventory of Vegetated Ecosystems	To gain information on composition, density, optical properties, and geometric structure of vegetation canopies and other surfaces using a combined lidar and stereo imager and a multi-angle global imager
103	Surface Observatories and in situ Observations in Support of Space-based Observations of Aerosols and Clouds	To monitor surface radiative fluxes and cloud and aerosol properties via a three-tiered system of surface-based observatories

RFI	Title	Brief Description of Objective
104	Terra-Luna: An Earth-Moon Science Exploration Mission	To construct a near-global baseline map of boreal and tropical forest land cover and biomass during multiple seasons, conduct first synoptic measurements of global ocean eddies, coastal currents and tides, and characterize land cover and canopy height for ecosystem and global climate modeling via L-band SAR and altimetry, then transfer to lunar orbit for lunar science measurements
105	Earth's First Time Resolved Mapping of Air Pollution Emissions and Transport from Space	To discover spatial and temporal emission patterns of the precursor chemicals for tropospheric ozone and aerosol transport across continents from GEO
106	Technology Coupling Innovative Observations to Test Forecasts in Order to Provide Decision Structures in Service to Society	To measure OH, HO_2, HDO/H_2O ratios, NO_2, H_2O, total H_2O, CH_4, N_2O, CO, CO_2, O_3, ClO, BrO, $BrONO_2$, ClOOCl, and $ClONO_2$ in order to bridge A-Train global observations with in situ detail via long-range, long-duration UAV observations
107	Water Vapor Monitoring Missions	To provide direct measurements of water vapor and other atmospheric constituents in the region of the tropical atmosphere extending from about 14 km (upper troposphere) to 35 km via long-life stratospheric balloons
108	Water Elevation Recovery Satellite Mission	To acquire elevations of inland water surfaces at spatial and temporal scales necessary for answering key water cycle and water management questions of global importance via swath-based altimetry
109	Wind Imaging Spectrometer and Humidity-sounder (WISH): a Practical NPOESS P3I High-spatial Resolution Sensor	To measure tropospheric winds by tracking high spatial resolution altitude-resolved water vapor sounding features via a wind imaging spectrometer and humidity-sounder
110	Climate-Quality Observations from Satellite Lidar	To continue lidar cloud observation data record after CALIPSO for climate change recognition
111	Advanced ICESat (Ice Cloud and Land Elevation Satellite)	To provide/determine polar ice-sheet mass balance; sea-ice freeboard and thickness; high-latitude oceanography and global sea level change; atmosphere-cloud heights and aerosol distributions; land topography referenced to a globally-consistent datum; vegetation-canopy heights and structure; river stage and discharge and lake and wetland water storage; glaciers and ice cap dynamics and mass balance, via laser altimeter.

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Biographical Information for Committee Members and Staff

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

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

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

SUSAN K. AVERY joined the University of Colorado faculty in 1982. In 2004 she was asked to serve as interim vice chancellor for research and dean of the Graduate School, a position to which she has returned after serving for 16 months as interim provost. Prior to this position, she served as director of the Cooperative Institute for Research in Environmental Sciences (CIRES) for 10 years. She is a professor of electrical and computer engineering and also serves as a fellow in CIRES. Her interdisciplinary interests include radar studies of atmospheric circulations and precipitation, climate information and decision support, and science communication. The author or co-author of over 80 articles in the refereed literature, she is a fellow in the Institute of Electrical and Electronics Engineers and the American Meteorological Society, of which she also served as president. University of Colorado awards include the Robert L. Stearns Award, recognition for exceptional achievement and/or service; the Elizabeth Gee Memorial Lectureship Award for scholarly contributions, distinguished teaching, and advancing women in the academic community; and the Margaret Willard Award for outstanding contributions to the University of Colorado at Boulder. The University of Illinois recently recognized her by awarding her the Distinguished Ogura Lectureship and the LAS Alumni Achievement Award. Dr. Avery's NRC service includes the Committee on NOAA NESDIS Transition from Research to Operations (vice chair, 2002-2004) and the Board on Atmospheric Sciences and Climate (1997-2001). She currently serves as a member of the Committee on Strategic Guidance for NSF's Support of the Atmospheric Sciences.

ERIC J. BARRON is dean of the Jackson School of Geosciences at the University of Texas at Austin, where he holds the Jackson Chair in Earth System Science. Prior to this appointment, he was dean of the College of Earth and Mineral Sciences at The Pennsylvania State University. Dr. Barron's research interests are in the areas of climatology, numerical modeling, and Earth history. During his career, he has worked diligently to promote the intersection of the geological sciences with the atmospheric sciences and the field of earth system science. Dr. Barron chaired the Science Executive Committee for NASA's Earth Observing System and NASA's Earth Science and Applications Advisory Committee (ESSAC). He has also served as chair of the USGCRP Forum on Climate Modeling, the Allocation Panel for the Interagency Climate Simulation Laboratory, the U.S. National Committee for PAGES and the NSF Earth System History Panel. For the NRC, Dr. Barron has served on the Climate Research Committee (chair, 1990-1996); In 1997, he was named co-chair of the Board on Atmospheric Sciences (co-chair, 1997; chair 1999-present); the Committee on Global Change Research, the Assessment of NASA Post-2000 Plans, Climate Change Science, the Human Dimensions of Global Change, the Panel on Grand Environmental Challenges, and the Committee on Tools for Tracking Chemical, Biological, and Nuclear Releases in the Atmosphere: Implications for Homeland Security. Dr. Barron is a fellow of the AGU, the American Meteorological Society, and the American Association for the Advancement of Science (AAAS). In 2002, he was named a fellow of the National Institute for Environmental Science at Cambridge University. In 2003, he received the NASA Distinguished Public Service Medal.

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

RUTH DeFRIES is a professor at the University of Maryland, College Park, with 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 at 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 is a member of the National Academy of Sciences. She is currently serving as a chair of the NRC Committee on Earth System Science for Decisions about Human Welfare: Contributions of Remote Sensing, and as a member of the Geographical Sciences Committee and the U.S. National Committee on Scientific Committee on Problems of the Environment. Dr. DeFries has taught at the Indian Institute of Technology in Bombay. She is a fellow of the Aldo Leopold Leadership Program.

WILLIAM B. GAIL is director of Strategic Development within Virtual Earth at Microsoft Corporation, with responsibility for expanding the capabilities of Virtual Earth and its use throughout the community. He was previously vice president of the Mapping and Photogrammetric Solutions division at Vexcel Corporation (acquired in 2006 by Microsoft), where he directed a global organization responsible for a range of Earth information systems and services. Prior to joining Vexcel, he was director of Earth Science Advanced Programs at Ball Aerospace where he led the development of spaceborne instruments and missions for Earth science and meteorology. Dr. Gail received his undergraduate degree in physics and his Ph.D. in electrical engineering from Stanford University, focusing his research on wave-particle interactions in Earth's magnetosphere. During this period, he spent a year as cosmic ray and upper atmospheric field scientist at South Pole Station. Dr. Gail is on the board of directors of Peak Weather Resources, Inc., is a member of the editorial boards for *Imaging Notes* magazine and the *Journal of Applied Remote Sensing*, and is the director of industry relations for the IEEE Geoscience and Remote Sensing Society. He has served on the following NRC studies: the Committee on Earth Studies (2002-2005), the Task Group on Principle Investigator-Led Earth Science Missions (2001-2003), the Committee on NASA-NOAA Transition from Research to Operations (2002-2003), the Committee to Review the NASA Earth Science Enterprise Strategic Plan (2003), and the NASA Earth Science and Applications from Space Strategic Roadmap Committee (2005).

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

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

ANTHONY C. JANETOS 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. Prior to this, 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 program. 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 ecological and environmental topics, including air pollution effects on forests, climate change impacts, land-use change, ecosystem modeling, and the global carbon cycle. He was a co-chair of the U.S. National Assessment of the Potential Consequences of Climate Variability and Change, and an author in the IPCC Special Report on Land-Use Change and Forestry, and the Global Biodiversity Assessment. Dr. Janetos recently served on the NRC Committee for Review of the U.S. Climate Change Science Program Strategic Plan and was a member of the Committee on Review of Scientific Research Programs at the Smithsonian Institution (2002).

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

NEAL F. LANE is the Edward A. and Hermena Hancock Kelly University Professor at Rice University. He also holds appointments as senior fellow of the James A. Baker III Institute for Public Policy, where he is engaged in matters of science and technology policy, and in the Department of Physics and Astronomy, and he previously served as university provost. Dr. Lane is a nationally recognized leader in science and technology policy development and application. He has previously served as Assistant to the President for Science and Technology, director of the White House Office of Science and Technology Policy, director of the National Science Foundation, and chancellor of the University of Colorado at Colorado Springs. Dr. Lane is a fellow of the American Physical Society, the American Academy of Arts and Sciences, the AAAS, and the Association for Women in Science. He currently serves as chair of the NRC Committee on Transportation of Radioactive Waste, and he is also a member of the Policy and Global Affairs Committee.

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

BRUCE D. MARCUS is retired from TRW, where he was chief scientist and manager of Advanced Programs for the Space and Laser Programs. Dr. Marcus's professional interests include space and Earth sciences. His research background includes heat and mass transfer, heat pipes, thermosiphons, spacecraft thermal control, and thermo-mechanical design of telescopes. Dr. Marcus and Aram Mika (former NRC Committee on Earth Studies member) were the key authors of the 2000 NRC report *The Role of Small Satellites in NASA and NOAA Earth Observation Programs*. Dr. Marcus was also a key consultant on technology issues related to the potential to use the NPOESS weather satellite for climate research, the subject of several recent NRC reports. Dr. Marcus's background also includes extensive experience in space systems program management. He served on the NRC Committee on Earth Studies (2003-2004 and 1995-1999), the Space Studies Board (2000-2004), the Task Group on Principal Investigator-Led Earth Science Mission (2000-2003), the Committee to Review the NASA Earth Science Enterprise Strategic Plan (2003), and the Task Group on Technology Development in NASA's Office of Space Science (1999-2000).

WARREN M. WASHINGTON is a senior scientist and head of the Climate Change Research Section in the Climate and Global Dynamics Division at NCAR. After completing his doctorate in meteorology at Pennsylvania State University, he joined NCAR in 1963 as a research scientist. Dr. Washington's areas of expertise are atmospheric science and climate research and he specializes in computer modeling of Earth's climate. He serves as a consultant and advisor to a number of government officials and committees on climate-system modeling. From 1978 to 1984, he served on the President's National Advisory Committee on Oceans and Atmosphere. In 1998, he was appointed to the National Oceanic and Atmospheric Agency Science Advisory Board. In 2002, he was appointed to the Science Advisory Panel of the U.S. Commission on Ocean Policy and the National Academies of Science Coordinating Committee on Global Change. Dr. Washington's NRC service is extensive and includes membership on the Board on Sustainable Development (1995-1999), the Commission on Geosciences, Environment, and Resources (1992-1994), the Board on Atmospheric Sciences and Climate (1985-1988), and his service as chair of the Panel on Earth and Atmospheric Sciences (1986-1987). He is a member of the National Science Board and currently serves as the chair.

MARK L. WILSON is a professor of epidemiology, director of Global Health Program, and professor of ecology and evolutionary biology at the University of Michigan. His research and teaching cover the broad area of ecology and epidemiology of infectious diseases. After earning his doctoral degree from Harvard University in 1985, he worked at the Pasteur Institute in Dakar Senegal (1986-90), was on the faculty at the Yale University School of Medicine (1991-1996), and then joined the University of Michigan. Dr. Wilson's research addresses the environmental determinants of zoonotic and arthropod-borne diseases, the evolution of vector-host-parasite systems, and the analysis of transmission dynamics. He is an author of more than 120 journal articles, book chapters and research reports, and has served on numerous governmental advisory groups concerned with environmental change and health. Dr. Wilson has served on the NRC Committee on Emerging Microbial Threats to Health in the 21st Century (2001-2003), the Committee on Review of NASA's Earth Science Applications Program Strategic Plan (2002), and the Committee on Climate, Ecosystems, Infectious Diseases, and Human Health (1999-2001).

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

Consultant

STACEY BOLAND received her Ph.D. in mechanical engineering from California Institute of Technology in 2005. She is currently a systems engineer and mission architect in the Earth Mission Concepts group at California Institute of Technology's Jet Propulsion Laboratory. Dr. Boland has led numerous pre-Phase A Earth mission architecture studies, and has assisted in creating consensus summaries and reports from aerosol and air quality science community workshops. Recently, Dr. Boland provided systems engineering support to the OOI Project office in support of the NSF ORION in situ ocean observatory, and provided coordination and strategic planning assistance for International Polar Year efforts.

Staff

ARTHUR CHARO, study director, received his Ph.D. in physics from Duke University in 1981 and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. Dr. Charo then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a fellow from 1985 to 1988. From 1988 to 1995, he worked in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment (OTA). He has been a senior program officer at the Space Studies Board (SSB) of the National Research Council since OTA's closure in 1995 and supports the work of the Committee on Solar and Space Physics and the Committee on Earth Studies. Dr. Charo has directed some 30 studies, including the first NRC decadal survey in solar and space physics. He is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and was the American Institute of Physics Congressional Science Fellow from 1988 to 1989. He is the author of research papers in the field of 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).

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