

Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Resmitted Fing a Strategy to Mitigate the Impact of Sensor Descopes and Demanifests on the NPOESS and GOES-R Spacecraft, National Research Council ISBN: 0-309-12185-X, 190 pages, 8 1/2 x 11, (2008)

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Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft

Elements of a Strategy to Recover Measurement Capabilities

Lost in Program Restructuring

Committee on a Strategy to Mitigate the Impact of Sensor Descopes and Demanifests on the NPOESS and GOES-R Spacecraft

Space Studies Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

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This study is based on work supported by Contract NNH06CE15B between the National Academy of Sciences and the National Aeronautics and Space Administration and Contract DG133R07SE1940 between the National Academy of Sciences and the U.S. Department of Commerce's National Oceanic and Atmospheric Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the agencies that provided support for the project.

International Standard Book Number 13: 978-0-309-12184-2 International Standard Book Number 10: 0-309-12184-1

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Preface

In June 2007, the National Research Council (NRC) held a 3-day workshop, "Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft," in Washington, D.C., to discuss options to recover measurement capabilities, especially those related to climate research, that were lost following a congressionally mandated review completed in June 2006 (Nunn-McCurdy certification¹) of the NPOESS program and the September 2006 cancellation of the HES sensor on GOES-R. Some 100 scientists and engineers from academia, government, and industry attended the workshop, which gave participants a chance to consider and comment on a mitigation plan developed by NASA-NOAA as well as to explore options that were not included in the NASA-NOAA study. An NRC report on the workshop proceedings was released in prepublication form in September 2007.² By design, that report did not present findings or recommendations.

Shortly before the workshop, NASA and NOAA requested that a committee of the NRC separate from the workshop organizing panel be formed to carry out a short follow-on study that would perform the following tasks (see Appendix A):

- 1. Prioritize capabilities, especially those related to climate research, that were lost or placed at risk following recent changes to NPOESS and the GOES-R series of polar and geostationary environmental monitoring satellites; and
 - 2. Present strategies to recover these capabilities.

The present report, written by the ad hoc Committee on a Strategy to Mitigate the Impact of Sensor Descopes and Demanifests on the NPOESS and GOES-R Spacecraft, constitutes the NRC response to this request.

¹See U.S. House of Representatives Committee on Science and Technology, Hearing Charter, "The Future of NPOESS: Results of the Nunn-McCurdy Review of NOAA's Weather Satellite Program," June 8, 2006, available at http://gop.science.house.gov/hearings/full06/June%208/charter.pdf.

²The workshop report (National Research Council, *Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft: A Workshop Report*, The National Academies Press, Washington, D.C., 2008) is reprinted in Appendix B.

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:

Mark R. Abbott, Oregon State University,

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Ralph F. Milliff, Colorado Research Associates,

William B. Rossow, City University of New York,

Thomas H. Vonder Haar, Colorado State University, and

Steven C. Wofsy, Harvard University.

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

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Summary

The nation's next-generation National Polar-orbiting Operational Environmental Satellite System (NPOESS) was created by the Presidential Decision Directive/National Science and Technology Council (NSTC)-2 of May 5, 1994, that merged the military and civil meteorological programs into a single program. Within NPOESS, the National Oceanic and Atmospheric Administration (NOAA) is responsible for satellite operations, the Department of Defense (DOD) is responsible for major acquisitions, and the National Aeronautics and Space Administration (NASA) is responsible for the development and infusion of new technologies.

In 2000, the NPOESS program anticipated purchasing six satellites for \$6.5 billion, with a first launch in 2008. By November 2005, however, it had become apparent that NPOESS would overrun its cost estimates by at least 25 percent, triggering a Nunn-McCurdy review by the DOD. The results of that review were announced in June 2006; among the notable changes in the "certified" NPOESS program were the following:

- The planned acquisition of six spacecraft was reduced to four.
- The planned use of three Sun-synchronous orbits was reduced to two, with data from the European Meteorological Operational (MetOp) satellites provided by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) providing data for the canceled mid-morning orbit.
 - The launch of the first spacecraft, NPOESS C1, was delayed until 2013.
- Several sensors were canceled (in common parlance, "demanifested") or degraded ("descoped") in capability as the program was refocused on "core" requirements related to the acquisition of data to support numerical weather prediction. "Secondary" (non-core) sensors that would provide crucial continuity to certain long-term climate records, as well as other sensors that would have provided new measurement capabilities, were not funded in the certified NPOESS program.

Since the 1970s, NOAA has operated geostationary satellites that provide images and data on atmospheric, oceanic, and climatic conditions over the continental United States and Hawaii from ~22,000 miles above the equator. NOAA's next generation of geostationary weather satellites will commence with the launch of GOES-R in 2015.³ Originally, plans for this series included four satellites—GOES-R through GOES-U. However, in September

¹Presidential Decision Directive/NSTC-2, "Convergence of U.S.-Polar-Orbiting Operation Environmental Satellite Systems," May 5, 1994, available at http://www.ipo.noaa.gov/About/NSTC-2.html.

²See U.S. House of Representatives Committee on Science, Hearing Charter, "The Future of NPOESS: Results of the Nunn-McCurdy Review of NOAA's Weather Satellite Program," June 8, 2006, available at http://gop.science.house.gov/hearings/full06/June%208/charter.pdf.

³Following program changes in September 2006, it was announced that launch of the first spacecraft in the GOES-R satellite series would be delayed until December 2014. However, a reduction in funds included in the FY 2008 enacted budget resulted in an additional delay

2006, following significant cost growth and estimates that the total program cost would nearly double, ⁴ NOAA reduced the scope of the program, removed a key instrument on the spacecraft, the Hyperspectral Environmental Suite (HES), ⁵ and revised the procurement process so that only two satellites are guaranteed. ⁶

These events prompted a request from NASA and NOAA for two National Research Council (NRC) efforts. The first, a workshop titled "Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft" and held in Washington, D.C., on June 19-21, 2007, gave participants an opportunity to discuss options to recover measurement capabilities, especially those related to climate research, that were lost as a result of the Nunn-Mc-Curdy actions and the cancellation of the HES on GOES-R. Some 100 scientists and engineers from academia, government, and industry attended the workshop, commenting on a draft mitigation plan developed by NASA and NOAA⁷ as well as exploring options not included in the NASA-NOAA report. A prepublication version of the workshop report (NRC, 2008) was released in October 2007.

The second NRC effort, a study documented in the present report, builds on the information gathered at the June 2007 workshop. In their request for this study (Appendix A), NASA and NOAA asked that a committee of the NRC "prioritize capabilities, *especially those related to climate research*, that were lost or placed at risk following recent changes to NPOESS and the GOES-R series of polar and geostationary environmental monitoring satellites" [emphasis added].

The Committee on a Strategy to Mitigate the Impact of Sensor Descopes and Demanifests on the NPOESS and GOES-R Spacecraft understands "climate" to be "the statistical description in terms of the mean and variability of relevant measures of the atmosphere-ocean system over periods of time ranging from weeks to thousands or millions of years" (Climate Change Science Program and the Subcommittee on Global Change Research, 2003, p. 12). In the present study, the committee primarily considered climate-related physical, chemical, and biological processes that vary on interannual to centennial timescales. It is also important to note that the committee did not a priori assume a longer-duration measurement record would be assigned a higher priority than a shorter-duration measurement record. Instead, the committee considered each measurement's value to climate science in a more comprehensive sense as described in the section below on prioritization. The committee interprets the information needed for climate research broadly to be that which enables:

- Detection of variations in climate (through long-term records),
- Climate predictions and projections,⁸ and
- Improved understanding of the physical, chemical, and biological processes involved in climate variability and change.

until April 2015. See Chapter 4, "Procurement, Acquisition and Construction," in NOAA FY 2009 Budget Summary, available at http://www.corporateservices.noaa.gov/~nbo/09bluebook_highlights.html.

⁴The cost growth resulted in part from the risk reduction achieved by a deliberate shift from a 50 percent cost probability to the more conservative 80 percent probability, based on lessons learned from NPOESS.

⁵The Hyperspectral Environmental Suite consisted of two components: an advanced hyperspectral sounder and a coastal waters imager. The hyperspectral sounder was intended to greatly advance current operational geostationary sounding capability; its cancellation will instead end the long-term geostationary sounding record started by GOES-I. The coastal waters imager component was planned primarily to benefit coastal monitoring, management, and remediation applications.

⁶Oversight Hearing on the Government Accountability Office Report on NOAA's Weather Satellite Program Before the Committee on Science, U.S. House of Representatives, September 29, 2006, available at http://science.house.gov/publications/hearings_markups_details.aspx?NewsID=1194.

⁷Outlined in a presentation titled "Mitigation Approaches to Address Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals," available at http://www7.nationalacademies.org/ssb/ NPOESSWorkshop_Cramer_NRC_06_19_07_final.pdf and also reprinted in Appendix C of the June 2007 workshop report. A final version of the NASA-NOAA report has not been released; a widely cited December 11, 2006, draft was posted by Climate Science Watch at http://www.climatesciencewatch.org/file-uploads/NPOESS-OSTPdec-06.pdf.

⁸Prediction (climate) is a probabilistic description or forecast of a future climate outcome based on observations of past and current climato-logical conditions and quantitative models of climate processes (e.g., a prediction of an El Niño event) and projection (climate) is a description of the response of the climate system to an assumed level of future radiative forcing. Changes in radiative forcing may be due to either natural sources (e.g., volcanic emissions) or human-induced causes (e.g., emissions of greenhouse gases and aerosols, or changes in land use and land cover). Climate "projections" are distinguished from climate "predictions" in order to emphasize that climate projections depend on scenarios of future socioeconomic, technological, and policy developments that may or may not be realized (Climate Change Science Program and the Subcommittee on Global Change Research, 2003, p. 12).

SUMMARY 3

BOX S.1 Goals of the U.S. Climate Change Science Program

- **Goal 1:** Improve knowledge of Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change.
- Goal 2: Improve quantification of the forces bringing about changes in Earth's climate and related systems.
- **Goal 3:** Reduce uncertainty in projections of how Earth's climate and related systems may change in the future.
- **Goal 4:** Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes.
- **Goal 5:** Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

SOURCE: The U.S. Climate Change Science Program Factsheet, available at http://www.climatescience.gov/infosheets/factsheet3/CCSP-3-StratPlanOverview14jan2006.pdf.

In performing its prioritization, the committee was cognizant of the scientific importance of maintaining long-term records of climate forcing *and* improving understanding of the climate system through starting or continuing records of climate responses. It also recognized the challenges of finding an appropriate balance between observations of climate forcing and response on the one hand, and sustained observations and improved "process" understanding on the other. The committee notes that its interpretation of the research agenda for climate-related issues is consistent with the five goals of the U.S. Climate Change Science Program (Box S.1).

APPROACH TO AND SCOPE OF PRIORITIZATION

Conducted during its December 17-19, 2007, meeting, the committee's prioritization of capabilities lost in program restructuring was guided by the following overarching principles:

- The objective of the committee's deliberations would be to prioritize for the restoration of *climate* capabilities. For example, although a sensor with the capability to improve resolution of fast climate processes is of interest to both the weather forecasting and the climate research communities, it is the value to the latter that would inform the committee's ranking.
- The particular strategy for recovery and the cost of recovery of a measurement/sensor would not be a factor in the ranking.⁹
- Measurements/sensors on NPOESS would not be ranked against measurements/sensors on GOES-R; however, the criteria used in ranking measurements/sensors for either program would be identical.
- When it was relevant, the measurement objectives of a particular sensor, and not the sensor itself, would be the basis for consideration. Thus, for example, members of the committee considered the importance of radar altimetry to climate science, rather than the importance of the particular implementation of this capability on NPOESS, that is, the ALT instrument.

Prior to the meeting, one or more committee members with the requisite expertise was assigned the task of preparing a detailed review of the issues associated with the descoping or demanifesting of a particular NPOESS

⁹The committee did not have access to the ongoing NASA-NOAA study for OSTP that is examining the cost of various recovery strategies.

or GOES-R measurement capability, guided by questions 1 through 9, below. These questions, which were developed at the committee's first meeting, follow from the committee's interpretation of what constitutes climate science and the associated requirements for climate observations (see above); they allow a prioritization across the diverse information requirements for climate science, for example, long-term measurements, new measurements, measurements of climate forcings and responses, measurements to improve scientific understanding and reduce key uncertainties, and measurements to improve climate predictions. The questions are also consistent with the ranking criteria employed by the panels of the NRC *Earth Science and Applications from Space* decadal survey (NRC, 2007), although in that study societal benefits and cost considerations were included as ranking factors. ¹⁰

By design, the questions were open-ended in order to provoke a more nuanced discussion of the value of the measurements. For example, rather than merely listing the duration of the measurement records at risk as a proxy for value, the committee considered the value of a long-term record in a more holistic manner via questions 1 and 5, which in turn prompted an in-depth exploration of the value of the long-term record, the impact of the record on global climate studies, the relative impact/consequences of a gap in the record, the maturity of related data assimilation, and sensor heritage. Such an analysis was considered important in the prioritization process in order to appropriately balance the need to continue very-long-duration measurements with shorter-duration measurements. The former would benefit with better scores for measurement/sensor maturity and the value of maintaining the long-term record. The latter measurements, although perhaps less mature, might result in greater consequences associated with a prospective measurement gap (for example, those related to climate forcing/response parameters with larger uncertainties for which longer trend data can greatly constrain future climate predictions).

- 1. To what extent are the data used both to monitor and to provide a historical record of the global climate? Is there a requirement for data continuity? If so, discuss the consequences of a measurement gap.
- 2. To what extent is this measurement important in reducing "uncertainty"—for example, in reducing error bars in climate sensitivity forcing and monitoring? In making these judgments, refer also to the priorities of the Climate Change Research Program.
- 3. Consider the importance of the measurement's role in climate prediction and projections (forcing/response/sensitivity).
 - 4. To what extent is the measurement needed for reanalysis?
- 5. Describe the measurement's maturity—for example, its readiness to be assimilated into a particular model(s)—and its heritage. If discussing a sensor, discuss its technical maturity and heritage.
- 6. Are other sensors and ancillary data required to make the measurement useful? Is this measurement unique? Are there complementary international sensors? If so, please list them and assess their capabilities. Discuss any data issues you may be aware of.
- 7. To what extent are the data used by, for example, the Intergovernmental Panel on Climate Change and the Climate Change Science Program (in developing synthesis and assessment products)?
- 8. Provide a qualitative assessment of the measurement's role in contributing to an overall improved understanding of the climate system and climate processes.
 - 9. To what extent does the measurement contribute to improved understanding in related disciplines?

Following each reviewer presentation, committee members actively discussed the measurement objective under consideration in relation to each of the nine questions. The committee's prioritization was developed on the basis of numerical scoring of the importance of each measurement capability to the needs of the climate research community (questions 1-8) and the importance of the measurement to related disciplines (question 9). Each of the responses to questions 1 through 9 was given equal weight in determining an overall ranking.¹¹

The committee had extensive discussions regarding whether a simple average of committee member rankings of the responses to questions 1 through 9 should be used for an overall ranking, or whether rankings with respect

¹⁰See Box 2.2 in Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (NRC, 2007), p. 40.

¹¹The committee was aware of a similar prioritization exercise conducted by NASA and NOAA in late 2006/early 2007. NASA and NOAA reached a somewhat different prioritization, which the present committee attributes in large part to their giving additional weight to the factors noted in question 1, that is, measurement continuity and the importance of avoiding a data gap.

SUMMARY 5

to particular questions should be given more weight. In part because there was no consensus among committee members on how a particular weighting scheme might improve what was already a subjective evaluation (in mapping the study statement of task to the questions, and in assigning individual numerical rankings for each question), the committee determined that the use of an unweighted average was advisable. Given that the committee was not provided any information concerning costs, relative or absolute, for any of the proposed mitigations, its prioritization of measurement capabilities was based entirely on climate science value as determined by consideration of the nine questions above. Lacking the information by which to determine the financial implications of its recommendations, the committee did not include implementation costs in its rankings. The committee notes, however, that had costs been provided, a more far-reaching set of recommendations might have been developed in which cost/benefit was taken into consideration. It is also important to recognize that important nonscientific factors were not, by design, part of the committee's analysis.

Before restructuring, each of the lost or degraded measurement capabilities had been considered both practicable and of high importance. In the case of NPOESS, a tri-agency under-secretary-level executive committee provides overall program direction and ensures that both civil and national security requirements are satisfied. 12 GOES-R requirements had been established by NOAA following a formal process that determined and prioritized user requirements; various senior management committees oversaw this process. 13 As is evident in the "Highlights of Analysis" sections in Chapter 3, the committee also found great merit in each of the climate-related measurement capabilities under consideration. However, given that a wholesale reversal of the programs' changes is not feasible, it became the committee's difficult task to provide a prioritized set of recommendations for restoration of climate measurement capabilities.

SUMMARY OF PRIORITIES AND MITIGATION OPTIONS

The committee prioritized all of the climate-related measurement capabilities that were lost or diminished as a result of NPOESS and GOES-R program restructuring rather than limiting its recommendations to the demanifested sensors as was done in the NASA-NOAA draft report prepared for the Office of Science and Technology Policy (OSTP). The committee's approach is consistent with input received from the community as part of the NRC's June 2007 workshop. Specifically, with respect to changes in the NPOESS program, the committee considered:

- Aerosol properties and the Aerosol Polarimetry Sensor (APS),
- Earth radiation budget and the Clouds and Earth's Radiant Energy System/Earth Radiation Budget Sensor (CERES/ERBS),
 - Hyperspectral diurnal coverage and the Cross-track Infrared Sounder (CrIS),
 - Microwave radiometry and the Conical Scanning Microwave Imager/Sounder (CMIS),
 - Ocean color and the Visible/Infrared Imager/Radiometer Suite (VIIRS),
 - Ozone profiles and the Ozone Mapping and Profiler Suite-Limb (OMPS-L) sensor,
 - Radar altimetry and the ALT sensor, and
- Total solar irradiance and the Total Solar Irradiance Monitor (TIM)/spectrally resolved irradiance and the Solar Spectral Irradiance Monitor (SIM).

With respect to the changes in the GOES-R program, the committee considered:

- Geostationary coastal waters imagery and the HES-CWI sensor, and
- Geostationary hyperspectral sounding and the HES sensor.

¹²Presidential Decision Directive/NSTC-2, "Convergence of U.S.-Polar-Orbiting Operation Environmental Satellite Systems," May 5, 1994, available at http://www.ipo.noaa.gov/About/NSTC-2.html.

¹³See Jim Gurka, "The Requirement Process in NOAA GOES-R Mission Definition," April 12, 2007, available at http://osd.goes.noaa.gov/documents/Requirements_Process.pdf.

¹⁴See footnote 7 above.

As a result of the prioritization process, the measurements and sensors listed above are divided into four groups, which the committee designates, in descending order of priority, as Tier 1 through Tier 4 (Figure S.1). As noted above, sensors from the NPOESS and GOES-R programs were not prioritized head-to-head. However, it can be roughly stated that considering climate science contributions alone, geostationary hyperspectral sounding compares to the NPOESS capabilities prioritized as Tier 2, and coastal waters imagery falls into Tier 4.

After completing the relative prioritization, the committee considered a wide range of options for recovery of the lost capabilities, including the remanifesting of sensors onto NPOESS platforms, accommodation of sensors on free flyers or flights of opportunity, and the use of formation flight to combine multiple, synergistic, measurement types without incurring the cost, complexity, and risk of large facility-class observatories. The committee's recommendations for mitigation recovery of the lost capabilities are detailed in the main text and are summarized in Table S.1.

The color coding used in Figure S.1 and Table S.1—green, yellow, blue, and pink shading to indicate Tier 1, Tier 2, Tier 3, and Tier 4 prioritization, respectively—is used as an interpretive aid in Chapter 3.

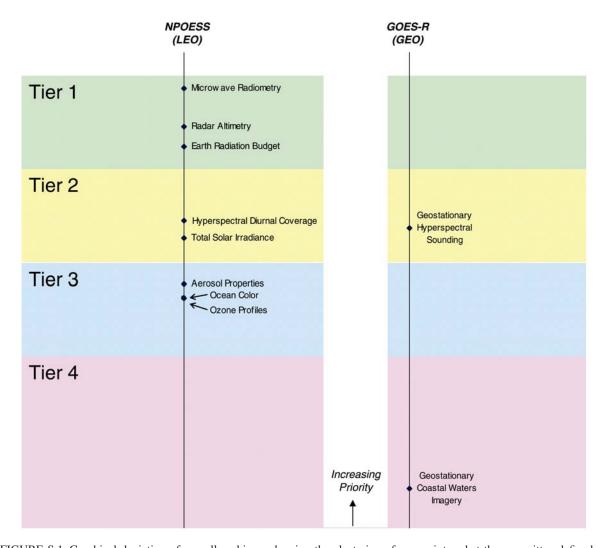


FIGURE S.1 Graphical depiction of overall rankings, showing the clustering of scores into what the committee defined as Tiers 1-4, for recovery of both NPOESS (low Earth orbit) and GOES-R (geostationary Earth orbit) lost or degraded climate capabilities.

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TABLE S.1 Summary Recommendations for Mitigation of Lost or Degraded Climate Capabilities

Lost or Degraded Climate Capability	Parameter defense
in NPOESS Low Earth Orbit	Recommendation
Tier 1 Microwave Radiometry	 NASA and NOAA should initiate a study as soon as practicable to address continuity of microwave radiometry and to determine a cost-effective approach to supplement the AMSR-2, carried on the Japanese spacecraft GCOM-W, with another microwave radiometer of similar design. The agencies should also consider the feasibility of manifesting a microwave radiometer on a flight of opportunity or free flyer to cover the microwave radiometry gap anticipated with a delay in accommodation of MIS until NPOESS C2. The agencies should provide funding for U.S. participation in an AMSR-2 science team to take full advantage of this upcoming microwave radiometer mission. The NPOESS Integrated Program Office should continue with its plans to restore a microwave sounder to NPOESS C2 and subsequent platforms, with an emphasis on SUAG priorities 1 through 3 (core radiometry, sounding channels, and soil moisture/sea surface temperature). NASA and NOAA should devise and implement a long-term strategy to provide sea-surface wind vector measurements. The committee finds important limitations in the planned reliance on a polarimetric radiometer for this measurement; instead, the preferred strategy is timely development and launch of the next-generation advanced scatterometer mission, that is, the Extended Ocean Vector Winds Mission (XOVWM) recommended in the 2007 NRC decadal survey Earth Science and Applications from Space.
Radar Altimetry	A precision altimetry follow-on mission to OSTM/Jason-2 (i.e., Jason-3) should be developed and launched in a time frame to ensure the necessary mission overlap. The agencies' long-term plan should include a series of precision altimetry free flyers in non-Sun-synchronous orbit designed to provide for climate-quality measurements of sea level.
Earth Radiation Budget	To minimize the risk of a potential data gap, the committee reiterates the recommendation of the 2007 Earth Science and Applications from Space decadal survey to manifest the CERES FM-5 on NPP. The agencies should further develop an ERB instrument series and provide for subsequent flights on Sun-synchronous platforms to continue the Earth radiation budget long-term record.
Tier 2	
Hyperspectral Diurnal Coverage	The CrIS/ATMS instrument suite should be restored to the 05:30 NPOESS orbit to provide improved hyperspectral diurnal coverage and support atmospheric moisture and temperature vertical profile key performance parameters.
Total Solar Irradiance	The agencies should consider use of an appropriate combination of small, low-cost satellites and flights of opportunity to fly TSIS (or at least TIM) as needed to ensure overlap and continuity of measurements of total solar irradiance.
Tier 3	
Aerosol Properties Ocean Color	 NASA should continue its current plan to fly the APS on Glory. NASA and NOAA should continue to mature aerosol remote sensing technology and plan for the development of operational instruments for accommodation on future platforms and/or flights of opportunity. The NPOESS Integrated Program Office should consider any practical mechanisms to
	 improve VIIRS performance for NPP and ensure that all specifications are met or exceeded by the launch of NPOESS C1. The agencies should ensure that adequate post-launch calibration/validation infrastructure is in place, including oversight by the scientific community, to ensure the production of viable ocean color imagery. To address reduced sensor coverage, the agencies should work with their international partners toward flying a fully functioning VIIRS or a dedicated sensor on a mission of opportunity in Sun-synchronous orbit. The agencies should also work with international partners to ensure community access to ocean color and ancillary calibration/validation data from international platforms during the gap likely to be experienced prior to launch of NPOESS C1.
Ozone Profiles	The committee supports current agency plans to reintegrate OMPS-Limb on NPP. The agencies should consider the relative cost/benefit of reintegration of OMPS-Limb capabilities for NPOESS platforms carrying OMPS-Nadir based on the degree of integration inherent in the instrument's original design.
Lost or Degraded Climate Capability in GOES-R Geostationary Earth Orbit	Recommendation
Tier 2 Geostationary Hyperspectral Sounding	NASA and NOAA should plan an earliest-possible demonstration flight of a geostationary hyperspectral sounder, supporting <i>operational</i> flight in the GOES-T time frame.
Tier 4 Geostationary Coastal Waters Imagery	Provision for coastal waters imaging should be considered by the agencies based on non-climate applications.

ELEMENTS OF A LONG-TERM CLIMATE STRATEGY: A WAY FORWARD

The committee has developed and recommends a prioritized, short-term strategy for recovery of crucial climate capabilities lost in the NPOESS and GOES-R program descopes. However, mitigation of these recent losses is only the first step in establishing a viable long-term climate strategy—one that builds on the lessons learned from the well-intentioned but poorly executed merger of the nation's weather and climate observation systems. The key elements of such a long-term strategy are discussed in Chapter 4 and are summarized here.

Sustained Climate Observations

In developing an effective long-term climate strategy, it is critical to consider the similarities in and differences between research, operational, and sustained measurements in order to take advantage of synergies when appropriate while avoiding incompatible observing system requirements. Sustained measurements needed to detect climate trends can, for example, impose tighter requirements for calibration, characterization, and stability, or impose orbit constraints different from what would otherwise be required for operational applications. A long-term climate strategy must provide for the essential characterization, calibration, stability, continuity, and data systems required to support climate applications.

National Policy for Provision of Long-Term Climate Measurements

Much of climate science depends on long-term, sustained measurement records. Yet, as has been noted in many previous NRC and agency reports, the nation lacks a clear policy to address these known national and international needs. For example, an ad hoc NRC task group (NRC, 1999b, p. 4) stated as follows:

No federal entity is currently the "agent" for climate or longer-term observations and analyses, nor has the "virtual agency" envisioned in the [U.S. Global Change Research Program] succeeded in this function. The task group endorses NASA's call for a high-level process to develop a national policy to ensure that the long-term continuity and quality of key data sets required for global change research are not compromised in the process of merging research and operational data sets.¹⁵

A coherent, integrated, and viable long-term climate observation strategy should explicitly seek to balance the myriad science and applications objectives basic to serving the variety of climate data stakeholders. The program should, for example, consider the appropriate balance between (1) new sensors for technological innovation, (2) new observations for emerging science needs, (3) long-term sustainable science-grade environmental observations, and (4) measurements that improve support for decision makers to enable more effective climate mitigation and adaptation regulations (NRC, 2006). The various agencies have differing levels of expertise associated with each of these programmatic elements, and the long-term strategy should seek to capitalize on inherent organizational strengths where appropriate. Elements of this needed national policy include clear roles and responsibilities for agencies, international coordination, and community involvement in the development of climate data records.

Clear Agency Roles and Responsibilities

In the NRC decadal survey *Earth Science and Applications from Space*, the authors stated, "The committee is concerned that the nation's civil space institutions (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

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¹⁵A similar view was expressed in *Adequacy of Climate Observing Systems*, which stated, "There has been a lack of progress by the federal agencies responsible for climate observing systems, individually and collectively, toward developing and maintaining a credible integrated climate observing system" (NRC, 1999a, p. 5).

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by mechanisms for cooperation. These are issues whose solutions will require action at high levels of the federal government" (NRC, 2007, p. 13). In turn, this prompted one of the report's most important recommendations: "The Office of Science and Technology Policy, in collaboration with the relevant agencies and in consultation with the scientific community, should develop and implement a plan for achieving and sustaining global Earth observations. This plan should recognize the complexity of differing agency roles, responsibilities, and capabilities as well as the lessons from implementation of the Landsat, EOS, and NPOESS programs" (p. 14). The present committee fully endorses the need for clarified agency roles and responsibilities, consistent with inherent agency strengths, and reiterates this important recommendation of the decadal survey.

International Coordination

The committee recognizes the importance of international cooperation in obtaining climate-quality measurements from space; the absence of an internationally agreed upon and ratified strategy for climate observations from space remains an area of grave concern. The research and operational agencies should coordinate their development, operations, standards, and products with international partners.

Community Involvement in the Development of Climate Data Records

The NRC has produced a number of reports on the subject of climate data records (CDRs), many having been motivated by concerns over the future availability of satellite-based climate-quality data records. The implied demise of climate-focused satellite observations from NPOESS, a consequence of the Nunn-McCurdy certification, adds to the ongoing concern about the lack of organized commitment to CDR development. It has been stressed in many NRC and other reports that generation of CDRs requires considerable scientific insight, including the blending of multiple sources of data; error analysis; and access to raw data. On the basis of its review of previous NRC studies and its own experience, the committee identified a number of particularly important elements for a sustained long-term program dedicated to developing credible CDRs. These elements are discussed in Chapter 4.

Finally, it is important to note that community concerns about the adequacy of NPOESS for climate research existed even before the 2006 program restructuring. For example, in the 2007 NRC decadal survey *Earth Science and Applications from Space* (NRC, 2007, p. 263), the report from the Panel on Climate Variability and Change concluded that, "Regardless of the descoping, the NPOESS program lacks essential features of a well-designed climate-observing system."

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Context

NPOESS AND GOES-R IN RELATION TO CLIMATE RESEARCH

The nation's next-generation National Polar-orbiting Operational Environmental Satellite System (NPOESS) was created by the Presidential Decision Directive/National Science and Technology Council (NSTC)-2 of May 5, 1994, that merged the military and civil meteorological programs into a single program. Within NPOESS, the National Oceanic and Atmospheric Administration (NOAA) is responsible for satellite operations, the Department of Defense (DOD) is responsible for major acquisitions, and the National Aeronautics and Space Administration (NASA) is responsible for the development and infusion of new technologies. In 2000, the NPOESS program anticipated purchasing six satellites for \$6.5 billion, with a first launch in 2008. However, by November 2005, it had become apparent that NPOESS would overrun its cost estimates by at least 25 percent, triggering a so-called Nunn-McCurdy review by the DOD.

In June 2006, a restructured—Nunn-McCurdy "certified" —NPOESS program was announced. Among the most important changes to the NPOESS program (see Figures 1.1 and 1.2) were the following:

- The planned acquisition of six spacecraft was reduced to four.
- The planned use of three Sun-synchronous orbits was reduced to two, with data from the European Meteorological Operational (MetOp) satellites provided by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) providing data for the canceled mid-morning orbit.
 - The launch of the first spacecraft, NPOESS C1, was delayed until 2013.
- Several sensors were canceled or descoped in capability as the program was refocused on "core" requirements related to the acquisition of data to support numerical weather prediction. "Secondary" (non-core) sensors that would provide crucial continuity to certain long-term climate records, as well as other sensors that would have provided new measurement capabilities, are not funded in the certified NPOESS program.³

¹Presidential Decision Directive/NSTC-2, "Convergence of U.S.-Polar-Orbiting Operation Environmental Satellite Systems" May 5, 1994. Available at http://www.ipo.noaa.gov/About/NSTC-2.html.

²See U.S. House of Representatives Committee on Science, Hearing Charter, "The Future of NPOESS: Results of the Nunn-McCurdy Review of NOAA's Weather Satellite Program," June 8, 2006, available at http://gop.science.house.gov/hearings/full06/June%208/charter.pdf.

³The NPOESS certified program now includes the following sensors: Visible/Infrared Imager/Radiometer Suite (VIIRS); Microwave Imager/Sounder (MIS); Search and Rescue Satellite Aided Tracking (SARSAT); Cross-track Infrared Sounder (CrIS); Advanced Technology Microwave Sounder (ATMS); Advanced Data Collection System (ADCS); Clouds and Earth's Radiant Energy System (CERES); Ozone

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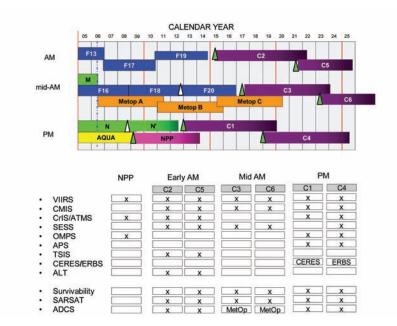


FIGURE 1.1 The NPOESS Preparatory Project and NPOESS program summary prior to the June 2006 Nunn-McCurdy program review and revisions. With the exception of CrIS, ATMS, and SESS, all key operational instruments, including SARSAT and ADCS, were intended to be flown on all three orbits. Climate and research-oriented sensors were generally designated a spot on a single satellite at any one time. The overall NPOESS constellation was designed as a stand-alone system, with the European series of MetOp satellite viewed as a separate, independent, complementary system. SOURCE: Courtesy of NOAA.

Costs for NOAA's next generation of geostationary weather satellites, GOES-R, had also risen dramatically, and in September 2006 NOAA canceled plans to incorporate a key instrument on the spacecraft—HES (Hyperspectral Environmental Suite). HES consisted of two components: an advanced hyperspectral sounder and a coastal waters imager. The hyperspectral sounder was intended to greatly advance current operational geostationary sounding capability; its cancellation will instead end the long-term geostationary sounding record started by GOES-I. The coastal waters imager component was planned primarily to benefit coastal monitoring, management, and remediation applications. The complexity associated with combining both the hyperspectral sounding and the coastal waters imagery components into a single instrument is frequently cited as the key factor affecting programmatic risk for GOES-R.

In this report, the ad hoc Committee on a Strategy to Mitigate the Impact of Sensor Descopes and Demanifests on the NPOESS and GOES-R Spacecraft reviews these recent changes to the NPOESS and GOES-R program and, as requested by NASA and NOAA (see Appendix A):

- 1. Prioritizes capabilities, especially those related to climate research, that were lost or placed at risk following recent changes to NPOESS and the GOES-R series of polar and geostationary environmental monitoring satellites; and
 - 2. Presents strategies to recover these capabilities.

In preparing this report, the committee drew heavily on information gathered at a 3-day National Research Council (NRC) workshop, "Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft,"

Mapping and Profiler Suite (OMPS)-Nadir; and the Space Environment Monitor (SEM). The certified program does not fund the following sensors: Aerosol Polarimetry Sensor (APS), Total Solar Irradiance Sensor (TSIS); OMPS-Limb; Earth Radiation Budget Sensor (ERBS); Altimeter (ALT); Survivability Sensor (SuS); and Full Space Environment Sensors (SESS). At the time the Nunn-McCurdy certified program was announced, it was also stated that the program would plan for and fund the integration of the demanifested sensors onto the satellite buses, if the sensors were provided from outside the program.

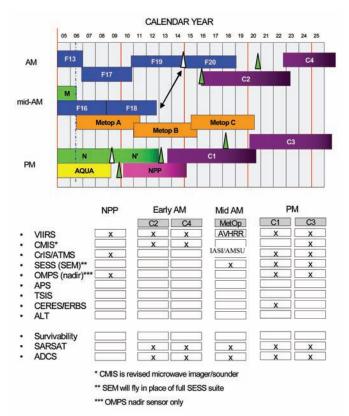


FIGURE 1.2 The NPOESS Preparatory Project and NPOESS program summary following the Nunn-McCurdy program review and revisions (status as of October 2006). The mid-morning satellite coverage will be provided by the European MetOp satellite series, with descoped NPOESS satellites covering the early morning and afternoon orbits. Instruments removed from the core NPOESS program plan can be integrated and flown if outside funding will support the remaining development costs, as well as the cost of the instrument and its support. The canceled CMIS sensor will be replaced by a sensor now known as MIS. Although its specifications are not yet known, MIS will by design be a less expensive instrument with less developmental risk. SOURCE: Courtesy of NOAA.

held in June 2007 in Washington, D.C. (referred to in this report as the June 2007 workshop). The NRC report on that workshop (NRC, 2008) is reprinted in Appendix B. For convenience, the issues that were of particular concern to workshop participants are reprinted in Box 1.1.

INPUT FROM NASA AND NOAA

Among the key inputs to the NRC's June 2007 workshop were presentations by NASA and NOAA officials, especially "Mitigation Approaches to Address Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals," which was derived from a NASA-NOAA draft report, "Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals," referred to below as the NASA-NOAA study. The authors of the NASA-NOAA draft report envisioned a multistep study process that would lead to a

⁴Available at http://www7.nationalacademies.org/ssb/NPOESSWorkshop_Cramer_NRC_06_19_07_final.pdf and also reprinted in Appendix C of the June 2007 workshop report.

⁵A final version of the NASA-NOAA report has not been released; a widely cited December 11, 2006, draft was posted by Climate Science Watch at http://www.climatesciencewatch.org/file-uploads/NPOESS-OSTPdec-06.pdf.

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NASA-NOAA roadmap by the end of 2007. Unfortunately, that work had not been completed as of the time this committee's report went to press, nor were drafts or conclusions of the study made available to the committee (because of those conclusions' connection to information embargoed pending announcement of the President's fiscal year 2009 budget).

By design, the NASA-NOAA study focused narrowly on impacts of the Nunn-McCurdy NPOESS program certification on two climate-research-related objectives:

- 1. Flight of critical climate sensors that had been planned for NPOESS and that represent the continuation of NASA's Earth Observing System (EOS) capabilities, and
- 2. Flight of those sensors that represent a fundamental contribution to NOAA's climate mission and that include both heritage satellite and in situ observing systems.

However, as stated in the NASA-NOAA draft report itself, the analysis did not consider the agencies' broader mandates, nor did it consider international contributions beyond those already identified in the European MetOp (Meteorological Operational satellite) program. In addition, the analysis focused primarily on options to remanifest sensors on NPOESS or on free-flyer spacecraft, with less attention given to options to mitigate the impacts of descoping of the remaining sensors, or to the impacts resulting from elimination of the originally planned NPOESS mid-morning orbit. The authors of the NASA-NOAA report completed their initial work prior to the January 2007 release of the NRC decadal survey report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (NRC, 2007); consequently, they could not analyze either the potential contributions of survey-recommended missions or the potential to remanifest certain sensors on survey-recommended spacecraft.

In October 2007, NASA, NOAA, and Integrated Program Office representatives briefed the committee to provide updates on the status of the various instruments and study activities.⁶ However, the results of preliminary studies undertaken by the agencies to examine the feasibility of remanifesting selected NPOESS sensors on future decadal-survey-recommended missions were not made available to the committee. Further, the specifications for a key instrument, the Microwave Imager and Sounder (MIS), had not yet been announced at the time the present report went to press. These information gaps did not detract from the committee's science-based prioritization of the climate research capabilities to be recovered from those lost as a result of NPOESS program restructuring; however, they obviously restricted the committee's analysis of mitigation strategies.

ONGOING COMMUNITY CONCERN

It is important to note that community concerns about the adequacy of NPOESS for climate research existed even before the 2006 program restructuring, as is evident, for example, in the NRC decadal survey on Earth science and applications from space (NRC, 2007), which includes the following statement (at p. 263) from the Panel on Climate Variability and Change:

Regardless of the descoping, the NPOESS program lacks essential features of a well-designed climate-observing system:

NPOESS lacks a transparent program for monitoring sensor calibration and performance and for verifying the
products of analysis algorithms. Moreover, it lacks the direct involvement of scientists who have heretofore played
a fundamental role in developing climate-quality records from space-borne observations. NOAA has initiated
plans for scientific-data stewardship (NRC, 2004b), but the plans are in their infancy, and NOAA's commitment
to ensuring high-quality climate records remains untested and inadequately funded (NRC, 2005).

⁶At the committee's October 2007 meeting, Bryant Cramer (NASA) and Michael Tanner (NOAA) provided an update on the NOAA-NASA remanifesting study, James Gurka (NOAA) provided an update on GOES-R HES recovery status, Stanley Schneider (NPOESS IPO) and Karen St. Germain (NPOESS IPO) provided updates on recent NPOESS program developments, and Jeffrey Privette (NOAA) discussed Climate Data Record generation activities. At the committee's December 2007 meeting, Maj. Christopher Brann (NPOESS IPO) and David Kunkee (Aerospace Corp.) briefed the committee on MIS procurement and status.

BOX 1.1 Summary of Issues Noted by June 2007 Workshop Participants

- Preservation of long-term climate records. Many participants noted that the demanifesting of climate sensors from NPOESS has placed many long-term climate records at risk, including multidecadal records of total solar irradiance, Earth radiation budget, sea surface temperature, and sea ice extent. Some of these most fundamental data records require observational overlap to retain their value and require immediate attention to ensure their continuation. To ensure continuity of critical long-term climate measurements, many participants also stressed the need to pursue international partnerships and, when feasible, the leveraging of foreign Earth observation missions.
- The potential benefits of relatively minor and low-cost changes to the NPOESS program. In several cases, a workshop participant suggested small nonhardware changes to NPOESS that could address areas of climate interest. Such changes included improving prelaunch characterization and documentation of all NPOESS instruments, adding minor software improvements to VIIRS¹ to make the data more climate-relevant, and downlinking full-resolution spectral data from the Cross-track Infrared Sounder (CrIS)² to enable creation of additional climate products.
- The potential role of spacecraft formation flying in mitigation strategies. Formation flight can allow for the synergistic combination of measurements from multiple satellites, sometimes launched years apart. To allow for subsequent formation flight with NPOESS platforms, some participants suggested consideration of the requisite orbit maintenance and operations requirements as part of the mitigation strategy for restoring deleted NPOESS and GOES-R climate observing capabilities.
- Mitigation options beyond changes to NPOESS. While particular long-term records can be secured via the remanifesting of certain sensors onto NPOESS, many participants noted that requirements for several could not be addressed even with the original suite of NPOESS instruments. Long-term records of sea level and ocean vector winds, for example, require different orbits and/or instruments to address critical climate observation needs. As a result, some participants heavily favored dedicated altimetry and scatterometry missions to fill this need. Further, some participants noted the critical importance of hyperspectral sounder measurements to climate science, suggesting restoration of CrIS/ATMS to the early-morning NPOESS orbit as well as the earliest-possible flight of a geostationary hyperspectral sounder to further improve temporal resolution.
- The challenge of creating climate data records. Although NPP- and NPOESS-derived environmental data records (EDRs) may have considerable scientific value, climate data records (CDRs)³ are far more than a time series of EDRs. Many participants at the workshop emphasized the fundamental differences between products that are generated to meet short-term needs (EDRs) and those for which consistency of processing and reprocessing over years to decades is an essential requirement (CDRs). Creation and maintenance of CDRs require
- 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 probably result in gaps of many months, which will make it difficult to connect long-term climate records and future measurements.
- The NPOESS commitment to 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. VIIRS may be flown as the NOAA AVHRRs were flown, with only preflight calibrations, leaving the in-orbit calibrations of those channels to drift. Furthermore, in its current configuration, VIIRS lacks the channels now on MODIS in the 6.7-µm band of water vapor used to detect winds in polar regions and in the 4.3- and 15-µm bands of CO₂ used to obtain cloud heights, particularly heights of relatively thin cirrus.
- NPOESS only partly addresses the needed measurements of the stratosphere and upper troposphere. The primary variables of the stratosphere—temperature, ozone abundance, and some aerosol properties—will not be provided

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algorithms, data-handling systems, calibration/validation, archival standards, access protocols, and prelaunch characterization that are different from those for operational data products.

- The specifications of the MIS instrument. The specifications of the MIS (Microwave Imager and Sounder) instrument on NPOESS, which is to replace the now canceled CMIS (Conical Microwave Imager and Sounder) instrument, were not known at the time of the workshop. Thus, participants were unable to fully analyze mitigation options. In addition, several participants warned about the consequences of not having an all-weather sea surface temperature retrieval capability, emphasizing the importance of retaining a low-frequency 6.9 GHz channel as the instrument is reconsidered.
- Sustaining climate observations. In the view of many participants, the loss of climate observations from NPOESS is of international concern and also imperils U.S. climate science leadership. Further, many participants noted that discussions at the workshop were focused on solving near-term climate measurement continuity issues, but that there would remain a longer-term problem of sustaining support for climate science. Issues noted included finding an appropriate balance between new and sustained climate observations and managing infusion of technology into long-term observational programs (including the challenges of doing so with a multi-spacecraft—block-buy—procurement). Workshop discussions also included what many participants cited as a key challenge: accommodating research needs within an operational program. Some participants argued that the relative priority of climate measurement needs would have to be heightened across the implementing agencies if climate and operational weather functions remain combined. Their concern was that in exploiting the commonalities of weather and climate observations, the unique needs of climate scientists would be overlooked. The perceived lack of attention to climate science needs within the Integrated Program Office, particularly calibration and validation requirements, led many participants to favor free-flyer options over integration with the NPOESS platforms.

SOURCE: NRC (2008), pp. 2-3.

by NPOESS, because of the loss of 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.

Perhaps the most important limitation of the NASA-NOAA study is its focus on near-term solutions to what are, in fact, structural problems associated with the provision of climate-quality measurements from systems designed to meet national objectives more closely associated with the needs of the operational weather forecast community. As discussed below in this report, and as noted repeatedly by participants in the June 2007 workshop, restoration of certain measurement capabilities is a necessary, but far from sufficient, step in a program to create climate-quality data records from satellite observations. The unique needs of the climate community have been discussed in many NRC reports (NRC, 2000a,b, 2004a,b, 2007, 2008). The problem of ensuring climate data re-

¹The Visible/Infrared Imager/Radiometer Suite (VIIRS) collects visible/infrared imagery and radiometric data. A key sensor on the NPOESS spacecraft, VIIRS contributes to 23 environmental data records (EDRs) and is the primary instrument associated with 18 EDRs. See description at http://www.ipo.noaa.gov/Technology/viirs_summary.html.

²In conjunction with the Advanced Technology Microwave Sounder (ATMS), the Cross-track Infrared Sounder (CrIS) collects atmospheric data to permit the calculation of temperature and moisture profiles at high temporal (~daily) resolution. See discussion at http://www.ipo.noaa.gov/Technology/cris_summary.html.

³See NRC, Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites, National Academy Press, Washington, D.C., 2000, and NRC, Climate Data Records from Environmental Satellites: Interim Report, The National Academies Press, Washington, D.C., 2004.

cords is embedded in larger issues of how to improve what has historically been a difficult and unpredictable path to transition NASA research capabilities to operational use (NRC, 2003). As noted in congressional testimony by a co-chair of the 2007 *Earth Science and Applications from Space* decadal survey:

There is a 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. The elimination of the requirements for climate research-related measurements on NPOESS is the most recent example of the failure to sustain critical measurements.⁷

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⁷Testimony of Richard A. Anthes before the Subcommittee on Space and Aeronautics Committee on Science and Technology, U.S. House of Representatives, June 28, 2007.

Prioritization of Lost Capabilities and Options for Short-Term Recovery

PRIORITIZATION PROCESS

Each of the measurement capabilities that was lost or degraded following NPOESS and GOES-R program restructuring had been previously considered both practicable and of high importance. In the case of NPOESS, a tri-agency under-secretary-level executive committee provides overall program direction and ensures that both civil and national security requirements are satisfied. GOES-R requirements were established by NOAA following a formal process that determined and prioritized user requirements; various senior management committees oversaw this process. As is evident in the "highlights of analysis" sections in Chapter 3, the committee also found great merit in each of the climate-related measurement capabilities under consideration. However, given that a wholesale reversal of the programs' changes is not feasible, it became the committee's difficult task to provide a prioritized set of recommendations for restoration of measurement capabilities.

In their request to the NRC, the study sponsors, NASA and NOAA, asked that a committee of the NRC "prioritize capabilities, especially those related to climate research, that were lost or placed at risk following recent changes to NPOESS and the GOES-R series of polar and geostationary environmental monitoring satellites" [emphasis added]. The committee understands "climate" to be "the statistical description in terms of the mean and variability of relevant measures of the atmosphere-ocean system over periods of time ranging from weeks to thousands or millions of years" (Climate Change Science Program and the Subcommittee on Global Change Research, 2003, p. 12). In the present study, the committee primarily considered climate-related physical, chemical, and biological processes that vary on interannual to centennial timescales. It is also important to note that the committee did not a priori assume a longer-duration measurement record would be assigned a higher priority than a shorter-duration measurement record. Instead, the committee considered each measurement's value to climate science in a more comprehensive sense as described below. The committee interprets the information needed for climate research broadly to be that which enables:

- Detection of variations in climate (through long-term records),
- Climate predictions and projections, and

¹Presidential Decision Directive/NSTC-2, "Convergence of U.S.-Polar-Orbiting Operation Environmental Satellite Systems" May 5, 1994, available at http://www.ipo.noaa.gov/About/NSTC-2.html.

²See Jim Gurka, "The Requirement Process in NOAA GOES-R Mission Definition," April 12, 2007, available at http://osd.goes.noaa.gov/documents/Requirements_Process.pdf.

BOX 2.1 Goals of the U.S. Climate Change Science Program

- **Goal 1:** Improve knowledge of Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change.
- Goal 2: Improve quantification of the forces bringing about changes in Earth's climate and related systems.
- **Goal 3:** Reduce uncertainty in projections of how Earth's climate and related systems may change in the future.
- **Goal 4:** Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes.
- **Goal 5:** Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

SOURCE: The U.S. Climate Change Science Program Factsheet, available at http://www.climatescience.gov/infosheets/factsheet3/CCSP-3-StratPlanOverview14jan2006.pdf.

• Improved understanding of the physical, chemical, and biological processes that are involved in climate variability and change.

In performing its prioritization, the committee was cognizant of the scientific importance of maintaining long-term records of forcing *and* improving understanding of the climate system through starting or continuing records of responses. It also recognized the challenges of finding an appropriate balance between observations of climate forcing and response, and between sustained observations and improved "process" understanding. The committee also notes that its interpretation of the research agenda for climate-related issues is consistent with the five goals of the U.S. Climate Change Science Program (Box 2.1).

The prioritization exercise was conducted during a December 17-19, 2007, meeting of the committee. The exercise was guided by the following overarching principles:

- The objective of the committee's deliberations would be to prioritize restoration of *climate* capabilities. For example, a sensor with the capability to improve resolution of fast climate processes is of interest to both the weather forecast and climate research communities; however, it is the value to the latter that informs the committee's ranking.
- The particular recovery strategy and the cost of recovery of a measurement/sensor would not be a factor in the ranking.³
- Measurements/sensors on NPOESS would not be ranked against measurements/sensors on GOES-R; however, the criteria used in the ranking would be identical.
- When it was relevant, judgments would be made according to the measurement objectives of a particular sensor, and not the sensor itself. Thus, for example, members of the committee considered the importance of radar altimetry to climate science, rather than the importance of the particular implementation of this capability on NPOESS, that is, the ALT instrument.

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³The committee did not have access to an ongoing NASA-NOAA study that is examining the costs of various recovery strategies.

Prior to the meeting, one or more committee members with the requisite expertise was assigned the task of preparing a detailed review of the issues associated with the descope or demanifest of a particular NPOESS or GOES-R measurement, guided by questions 1-9, below. These questions, which were developed at the committee's first meeting, follow from the committee interpretation of climate science and the associated needs for climate observations (see above); they allow a prioritization across climate science's various needs (for example, for long-term measurements, new measurements, measurements of climate forcings and responses, measurements to improve scientific understanding and reduce key uncertainties, and measurements to improve climate predictions). The questions are also consistent with the ranking criteria employed by the panels of the NRC *Earth Science and Applications from Space* decadal survey (NRC, 2007), although in that study societal benefits and cost considerations were included as ranking factors.⁴

By design, the questions were open-ended in order to provoke a more nuanced discussion of the value of the measurements. For example, rather than merely listing the duration of the measurement records at risk as a proxy for value, the committee considered the value of a long-term record in a more holistic manner via questions 1 and 5, which in turn prompted an in-depth exploration of the value of the long-term record, the impact of the record on global climate studies, the relative impact or consequences associated with a gap in the record, the maturity of related data assimilation, and sensor heritage. Such an analysis was considered important in the prioritization process in order to appropriately balance the needs to both continue very-long-duration measurements and provide for shorter-duration measurements with high climate impact. The former would benefit with better scores for measurement/sensor maturity and the value of maintaining the long-term record. The latter measurements, although perhaps less mature, might result in greater consequences associated with a prospective measurement gap (for example, those related to climate forcing or response parameters with larger uncertainties for which longer trend data can greatly constrain future climate predictions).

- 1. To what extent are the data used both to monitor and to provide a historical record of the global climate? Is there a requirement for data continuity? If so, discuss the consequences of a measurement gap.
- 2. To what extent is this measurement important in reducing "uncertainty"—for example, in reducing error bars in climate sensitivity forcing and monitoring? In making these judgments, refer also to the priorities of the Climate Change Research Program.
- 3. Consider the importance of the measurement's role in climate prediction and projections (forcing/response/sensitivity).
 - 4. To what extent is the measurement needed for reanalysis?
- 5. Describe the measurement's maturity—for example, its readiness to be assimilated into a particular model(s)—and its heritage. If discussing a sensor, discuss its technical maturity and heritage.
- 6. Are other sensors and ancillary data required to make the measurement useful? Is this measurement unique? Are there complementary international sensors? If so, please list them and assess their capabilities. Discuss any data issues you may be aware of.
- 7. To what extent are the data used by, for example, the Intergovernmental Panel on Climate Change and the Climate Change Science Program (in developing synthesis and assessment products)?
- 8. Provide a qualitative assessment of the measurement's role in contributing to an overall improved understanding of the climate system and climate processes.
 - 9. To what extent does the measurement contribute to improved understanding in related disciplines?

Following each reviewer presentation, committee members actively discussed each of the nine questions for the measurement need under consideration. Each committee member who was present then entered a numerical score from 1 (highest priority) to 5 (lowest priority) on a scorecard. After the final presentation, the scorecards were submitted and the results tallied. The committee's prioritization resulted from numerical scoring of the importance of these factors for the needs of the climate research community (questions 1-8) and the importance of

⁴See Box 2.2 in Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (NRC, 2007), p. 40.

the measurement to related disciplines (question 9). Each of the responses to questions 1-9 was given equal weight in determining an overall ranking.⁵

The committee had extensive discussions on whether a simple average of member rankings of the responses to Questions 1-9 should be used for an overall ranking, or whether rankings of particular questions should be given more weight. In part because there was no consensus among committee members on how a particular weighting scheme might improve what was already a subjective evaluation (mapping study statement of task to the questions; individual numerical rankings for each question), the committee determined that the use of an unweighted average was advisable. Further, as the committee was not provided any information concerning costs, relative or absolute, for any of the proposed mitigations, prioritization was based entirely on climate science value as determined by consideration of the nine questions above. The committee notes, however, that had costs been provided, a more far-reaching set of recommendations might have been developed in which cost/benefit was taken into consideration. Finally, it is important to recognize that important non-scientific factors were, by design, not part of the committee's analysis.

Climate Areas Impacted by NPOESS Changes

The committee considered the climate-related impacts of descopes to the NPOESS and GOES-R programs in a thematic context. For NPOESS, the committee considered:

- Aerosol properties and the Aerosol Polarimetry Sensor (APS),
- Earth radiation budget and the Clouds and Earth's Radiant Energy System/Earth Radiation Budget Sensor (CERES/ERBS),
 - Hyperspectral diurnal coverage and the Cross-track Infrared Sounder (CrIS),
 - Microwave radiometry and the Conical Scanning Microwave Imager/Sounder (CMIS),
 - Ocean color and the Visible/Infrared Imager/Radiometer Suite (VIIRS) sensor,
 - Ozone profiles and the Ozone Mapping and Profiler Suite-Limb (OMPS-L) sensor,
 - Radar altimetry and the ALT sensor, and
- Total solar irradiance and the Total Solar Irradiance Monitor (TIM); spectrally resolved irradiance and the Solar Spectral Irradiance Monitor (SIM).

For GOES-R, the committee considered:

- Geostationary Hyperspectral Sounding and the HES sensor, and
- Coastal waters imagery and the HES-CWI sensor.

The climate capability areas considered for prioritization are briefly described here (in alphabetical order), and are discussed in more detail in dedicated sections in Chapter 3.

Aerosol Properties

Tropospheric aerosols play a crucial role in climate and can cause a climate forcing directly by absorbing and reflecting sunlight, thereby cooling or heating the atmosphere, and indirectly by modifying cloud properties. The Aerosol Polarimetry Sensor (APS), eliminated following Nunn-McCurdy certification but originally planned to be included on the first and fourth NPOESS spacecraft, was intended to (1) measure the global distribution of natural and anthropogenic aerosols (e.g., black carbons, sulfates) with accuracy and coverage sufficient for reliable quantification of the effect of aerosols on climate, the anthropogenic component of the aerosol effect, and the

⁵The committee was aware of a similar prioritization exercise that had been conducted by NASA and NOAA in late 2006/early 2007. NASA and NOAA reached a somewhat different prioritization, which we attribute in large part to their giving additional weight to the factors noted in question 1, that is, measurement continuity and the importance of avoiding a data gap.

potential secular trends in the aerosol effect caused by natural and anthropogenic factors; (2) measure the direct impact of aerosols on the radiation budget and its natural and anthropogenic components; (3) measure the effect of aerosols on clouds (lifetime, microphysics, and precipitation) and its natural and anthropogenic components; and (4) investigate the feasibility of improved techniques for the measurement of black carbon and dust absorption to provide more accurate estimates of their contribution to the climate forcing function. The committee considered the originally planned measurements to determine relative prioritization of this lost climate measurement capability.

Earth's Radiation Budget

Along with incoming solar radiation, outgoing radiation helps establish Earth's radiant energy balance; the difference between the two corresponds to "climate forcing," which is exhibited in part by rising global average tropospheric temperatures. The CERES and ERBS sensors, which measure outgoing radiation, were designed to continue a data record from 1984 that is providing information on how energy from the Sun is absorbed and re-emitted by Earth, including the effects of human activities (such as the burning of fossil fuels and the use of chlorofluorocarbons) and natural occurrences (such as volcanic eruptions). These measurements are currently provided by the CERES instruments on the TRMM (1997), Terra (1999), and Aqua (2002) missions. Prior to the Nunn-McCurdy certification, the NPOESS program planned to place the last remaining CERES sensor, a flight spare from TRMM designated as FM-5, on the first NPOESS 13:30 orbit, with a launch in 2010, and then place ERBS on NPOESS C4 in 2015 and beyond. Following certification, the CERES FM-5 instrument was retained for NPOESS C1, which is now planned for launch in 2013, and all subsequent ERBS instruments were demanifested. The committee considered the originally planned measurements to determine a relative prioritization of this lost climate measurement capability.

Hyperspectral Diurnal Coverage

The Cross-track Infrared Sounder (CrIS) is an interferometric sounding sensor designed to measure upwelling Earth radiances at very high spectral resolution. Data from CrIS and another NPOESS sensor, ATMS (Advanced Technology Microwave Sounder), are used to construct vertical profiles of atmospheric temperature, moisture, and pressure. The certified NPOESS deletes CrIS and ATMS from the early AM (05:30 local solar time) orbit platforms, but retains the sensors on the PM orbit platforms (C1, launching in 2013, and C3, launching no earlier than 2018). The committee considered the importance of additional diurnal coverage to determine relative prioritization of this degraded climate capability.

Microwave Radiometry

The Conical Scanning Microwave Imager/Sounder (CMIS) sensor was canceled following NPOESS certification; it is in the process of being re-competed as a similar but less capable, less expensive, and less technologically risky sensor, designated MIS (Microwave Imager/Sounder). Prior to certification, CMIS was baselined for inclusion on each of the six NPOESS spacecraft, starting with C1 in 2010. Post-certification, CMIS is delayed until launch of the second NPOESS spacecraft, now scheduled for no earlier than 2016. CMIS/MIS will provide global microwave radiometry and sounding data to produce microwave imagery and other meteorological and oceanographic data. Data types include atmospheric temperature and moisture profiles, clouds, sea surface vector winds, and

⁶APS is an instrument on the Glory spacecraft. Its measurement objectives can be found on the Glory homepage at http://glory.gsfc.nasa.gov/overview-aps.html.

⁷CERES (Clouds and Earth's Radiant Energy System) consists of two broadband scanning radiometers that measure Earth's radiation balance and provide cloud property estimates to assess their role in radiative fluxes from the surface to the top of the atmosphere. See http://science.larc.nasa.gov/ceres/index.html.

⁸As this report went to press, additional delay (from 2009 to mid-2010) in the launch of the NPOESS Preparatory Project spacecraft was announced. To avoid a potential gap in Earth radiation budget measurements, NASA and NOAA officials were planning to move CERES FM-5 to the NPP platform from NPOESS C1.

all-weather land/water surfaces. The original CMIS was planned to contribute to 23 NPOESS environmental data records (EDRs) and was the primary instrument for nine EDRs. As noted, the reduced-capability MIS sensor will not be available for the first NPOESS platform. The committee considered the multitude of climate community microwave radiometry needs to determine relative prioritization of the likely measurement gap associated with deferral of this climate capability until the launch of NPOESS C2.

Ocean Color

The Visible/Infrared Imager/Radiometer Suite (VIIRS) will collect visible/infrared imagery and radiometric data (Lee et al., 2006). VIIRS will combine the radiometric accuracy of the Advanced Very High Resolution Radiometer (AVHRR) currently flown on the NOAA polar orbiters with the high spatial resolution of the Operational Linescan System (OLS) flown on the Air Force's Defense Meteorological Satellite Program (DMSP) spacecraft. The VIIRS instrument that is planned for launch on the NPP spacecraft is now considered unlikely to meet its design requirements for measurements of ocean color given that recent instrument tests show higher than anticipated optical cross-talk that will degrade instrument performance. Ocean color measurements are used to detect and monitor changes in water quality and ocean primary productivity, track harmful algal blooms, and assess underwater visibility for divers; they are also used in a variety of other applications related to ocean ecosystems, carbon and elemental cycling, coastal habitats, and coastal hazards (Siegel and Yoder, 2007; see Appendix C). The committee considered the impacts of the VIIRS sensor's degraded performance on ocean-color-related data products and prioritized the importance of restoring the degraded capabilities according to the climate-focused criteria enumerated above.

Ozone Profiles

The OMPS-Limb sensor, now demanifested from NPOESS, was to provide measurements of ozone vertical profiles, which are needed to understand and monitor the processes involved in the depletion and anticipated recovery of ozone in the stratosphere. Certification made no change to the OMPS-Nadir instrument, which measures total column ozone at nadir and continues the record from TOMS. The committee considered the originally planned OMPS-Limb measurements to determine relative prioritization of this lost climate capability.

Radar Altimetry

Because of the expense and the logistical and operational difficulties of obtaining globally distributed in situ oceanic observations, altimetry has been identified as the central element of major programs aimed at understanding the ocean's role in climate. The ALT instrument, demanifested from NPOESS following certification, was originally planned for flight on NPOESS C2 and C5. Prior to its elimination from NPOESS, data from ALT was planned to continue an unbroken record first established with the launch in 1992 of the TOPEX/Poseidon mission. This record was maintained with the launch of Jason-1 in 2001, and will continue with the launch of the Ocean Surface Topography Mission, also known as Jason-2, in 2008. However, as emphasized by many participants at the June 2007 workshop, the inclusion of ALT on NPOESS platforms, all of which will be in Sun-synchronous orbits, would likely prevent it from being able to provide data of the quality desired by the climate community. The committee thus considered the climate community's need for climate-quality precision radar altimetry measurements to determine relative prioritization of this lost climate capability.

⁹For example, the World Ocean Circulation Experiment (WOCE) and the Climate Variability and Predictability (CLIVAR) program of the World Climate Research Programme (WCRP). See "Report of the Altimeter Study Group to NASA Headquarters and the EOS Payload Panel," *The Earth Observer*, January/February, Vol. 7 No. 1, 1995. Available at http://eospso.gsfc.nasa.gov/eos_observ/1_2_95/p03.html.

¹⁰To compute ocean circulation from sea surface topography, the tidal component from the observed sea surface height must be subtracted, as even the best models of ocean tides have errors. ALT measurements from the NPOESS Sun-synchronous orbit would inherently be subject to aliasing from tidal activity, and thus inadequate to continue the precision altimetry record.

Total Solar Irradiance

TSIS consists of a total solar irradiance monitor (TIM) plus a solar spectral irradiance monitor (SIM). The TIM portion measures total solar irradiance (TSI), the integrated solar radiation incident at the top of Earth's atmosphere, in order to continue a climate record, unbroken since 1978, that is used to determine the sensitivity of Earth's climate to the natural effects of solar forcing. SIM continues the recently established, and thus relatively shorter, record of solar spectral irradiance (SSI) begun by SORCE (2002-). Prior to Nunn-McCurdy, TSIS was planned to fly on the original NPOESS early AM platforms C2 (2011) and C4 (2014). Nunn-McCurdy certification resulted in the demanifest of TSIS from NPOESS. The committee considered both TSI and SSI measurement needs to determine relative prioritization of this lost climate capability.

Climate Areas Impacted by GOES-R Changes

Coastal Waters Imagery

The coastal waters region is frequently defined as the 400 km zone adjacent to the continental United States. These waters are highly dynamic: tides, diurnal winds, river runoff, upwelling, and storm winds drive currents that range from 1 to approximately 3 m/s. Three-hour or better sampling is required to resolve these features and to track red tides, oil spills, or other features of concern for coastal environmental management. The Coastal Water Imager (CWI) was a proposed component of the Hyperspectral Environmental Suite (HES) that would be flown on the Geostationary Operational Environmental Satellite R Series (GOES-R) to acquire multispectral to hyperspectral visible/near-infrared images of Earth's surface at high spatial and temporal resolution. Its data would fill an existing gap in the time-space domain of available observations obtained from existing spaceborne sensors. The HES-CWI instrument was demanifested from GOES-R as a result of decisions announced in September 2006. The committee considered the originally planned coastal waters measurements to determine relative prioritization of this lost climate capability.

Geostationary Hyperspectral Sounding

Operational high-spectral-resolution infrared radiance measurements from the geostationary perspective were to be introduced on GOES-R with the HES (Hyperspectral Environmental Suite). The advanced hyperspectral sounder was planned to have more than 1,000 channels with narrow spectral widths compared to the current GOES sounders, which have only 18 much wider bands. In turn, HES would have provided substantially improved temperature and water vapor vertical profiles with higher accuracy and vertical resolution than are available with current sounder technologies. As noted above, the HES instrument was demanifested from GOES-R; the committee considered the originally planned geostationary hyperspectral measurements to determine relative prioritization of this lost climate capability.

NEAR-TERM MITIGATION OPTIONS

The following sections summarize the committee's analysis of near-term recovery and mitigation options for the climate-related measurements and associated sensors that were impacted by the changes following Nunn-Mc-Curdy certification and the cancelation of HES on GOES-R. It is important to note that the committee considered a range of options and did not limit its analysis to the practicality of simply restoring a demanifested or descoped sensor. The options studied included reintegration on NPOESS or GOES-R platforms, free-flyer missions, flights of opportunity, and leveraging international efforts. Because of the limitations noted above, the depth of the committee's analysis varies. The committee also emphasizes that the options discussed below are effectively only a first step—a necessary but far from sufficient condition—in establishing a viable long-term climate strategy.

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Reintegration on NPOESS Platforms

The committee was briefed on the agencies' proposed strategy to recover climate capabilities lost as a result of the NPOESS Nunn-McCurdy descoping. The proposed strategy centered heavily on the formation of a new series of free-flyer missions rather than restoration of the appropriate sensors to the NPOESS platforms. The high cost of reintegration and risk to NPOESS launch schedules were cited as the primary reasons for this approach.

It is somewhat surprising to the committee that the cost of reintegration is at issue, given that the satellites themselves were expressly designed to support the original payload suite and have not been descoped. While a dedicated line of free-flyer climate satellites is clearly attractive for its gap-filling capability and singular focus on climate needs, the committee is not convinced that the strategy put forth by the agencies adequately meets the breadth of needs of the climate science community, nor does it appear to be a cost-effective approach. The efficiency of establishing a new line of climate satellites versus restoration of certain sensors to NPOESS demands further consideration.

Free-Flyer Missions

As noted in the report from the June 2007 workshop (NRC, 2008a, p. 45):

The use of free-flying spacecraft to ensure the continuity of CDRs [climate data records] was frequently suggested as desirable by workshop participants. Free flyers provide increased launch flexibility, which decreases the risk of a gap in the measurements. It was considered noteworthy that none of the climate sensors are considered of sufficiently high priority for sensor failure to trigger the launch of a new NPOESS bus to preserve the data record. However, free flyers are not without risk, as they are typically more susceptible to cancellation compared with a single large, operational spacecraft bus. Some participants also noted that regardless of their desirability, NOAA has no history of utilizing free flyers as operational space platforms.

The use of smaller, comparatively less expensive platforms may facilitate technology insertion into an operational program. Free flyers also allow a spacecraft's orbit to be tailored to the requirements of a particular observation; however, in the very constrained budgetary environment that is anticipated for the foreseeable future, expenditures for free flyers might also have to compete against resources to implement the decadal survey mission recommendations (NRC, 2007). The decadal survey missions represent a set of community consensus priorities spanning Earth science including, but not limited to, climate science. *Mitigation strategies presented here were considered entirely within the context of climate measurement recovery, and are not to be construed as a review of decadal survey mission priorities.*

In order to support requirements for near-simultaneous observations, a free-flyer architecture might necessitate launching multiple spacecraft into a closely spaced formation. The principal benefit of formation flying is the ability to combine multiple, synergistic measurement types without incurring the cost, complexity, and risk of large facility-class observatories. There are, of course, operational challenges associated with formation flight (for example, maneuver coordination, orbit insertion, and end-of-life considerations), although these can be addressed through careful plans and procedures, and through taking advantage of the lessons learned through NASA's A-train¹² operations (Box 2.2). The opportunity for free flyers to orbit in formation, for example, with the NPOESS or the MetOp series, would provide greatly added flexibility to recover climate measurement capabilities for sensors that require co-aligned observations from other NPOESS sensors (e.g., ERBS requires ancillary

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¹¹NPOESS satellite bus capabilities were not descoped as part of Nunn-McCurdy certification and the recertified program retained funding within the NPOESS baseline for the reintegration of the demanifested sensors should a way be found to provide them from outside the program. See, for example, Statement of Dr. John Marburger, III, Director, Office of Science and Technology Policy, to the Committee on Science and Technology Subcommittee on Energy and Environment, United States House of Representatives, "Status Report on the NPOESS Weather Satellites," June 7, 2007. Available at http://science.house.gov/publications/Testimony.aspx?TID=6519.

¹²The "A-Train" satellite constellation consists of two of the major EOS missions, three ESSP missions, and a French Centre National d'Etudes Spatiales (CNES) mission flying in close proximity. See http://aqua.nasa.gov/doc/pubs/A-Train_Fact_sheet.pdf.

BOX 2.2 Formation Flight: The A-Train

Achieving formation flight with a diverse set of spacecraft, including the large EOS observatories, microsatellites, and international partner satellites—some launched years apart—required advances in both station-keeping ability and operational coordination. The ability to station-keep multiple satellites in their assigned boxes within the train—including satisfaction of footprint overlap requirements—is now operationally demonstrated. In September 2004, NASA published the "Afternoon Constellation Operations Coordination Plan," jointly written by all of the Constellation members to keep the A-Train Constellation (Figure 2.2.1) organized and safe.¹ To perform independent and coordinated measurements and thereby derive greater science value than that possible from the individual missions alone, each satellite operator must know the trajectory and mission operations plans for the other missions. In formation flying, the relative acceleration between satellites is estimated and used to plan maneuvers to give one satellite (e.g., CloudSat) the desired motion relative to another (e.g., CALIPSO).² Drag-make-up and inclination maneuvers must also be effected, as well as coping with anomalous situations.

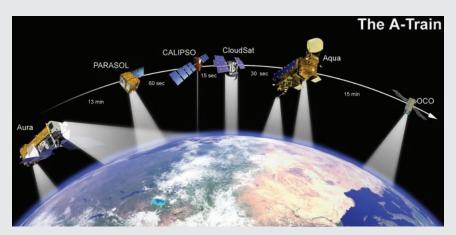


FIGURE 2.2.1 The A-Train, on-orbit today, including the future OCO mission. SOURCE: Courtesy of NASA.

There are many advantages of formation flight:

- The degree of simultaneity can be assigned based upon position within the formation.
- The formation can be permanent, with its composition changing over time.
- · International cooperation is facilitated.
- Technology insertion is facilitated.
- · Individual sensor replacement is facilitated.
- · Synergies can be achieved.

The A-Train was formed around the large EOS Aqua and Aura observatories. In the NPOESS era, such trains might be centered around the NPP, MetOp, and NPOESS spacecraft—and lower-inclination missions. Standard buses capable of carrying several instruments, which exist in spacecraft catalogs, can readily accommodate various combinations of operational weather and climate instruments.

¹Afternoon Constellation Operations Coordination Plan, prepared by Angelita C. Kelly/GSFC Constellation Team Manager, Ron Boain/JPL CloudSat Project Engineer, Karen Richon/GSFC ESMO Constellation Flight Dynamics Lead, and Mary Elizabeth Wusk/LaRC CALIPSO Ground System Manager, Earth Science Mission Operations Project, NASA/GSFC, September 2004.

²D.E. Keenan, A Formation Flying Strategy for CloudSat/Picasso-Cena (CALIPSO), *IEEE Proceedings* 2:535-552, 2001.

data from a multispectral imager such as VIIRS). With attention to the requisite orbit maintenance and operations requirements, NASA and NOAA should be able to include formation flying as a deliberate part of a mitigation strategy for restoring NPOESS and GOES-R climate-observing capabilities.

Flights of Opportunity

In some cases, sensors can be manifested on already-planned missions to capitalize on surplus satellite performance capability. Flights of opportunity might leverage planned NASA or NOAA missions, or take advantage of so-called secondary-payload capability on planned commercial flights. Repeated commercial flights, such as those of Intelsat (GEO) and Iridium NEXT (LEO), offer potential opportunities for one-of-a-kind or extended lines of climate instruments to be flown at negotiated costs.

Each platform will bring its own electromagnetic interference environment, pointing control and knowledge capabilities, and accommodation parameters. And each provider will have tight timelines, presenting a challenge to government programs when decision making and procurement occur over years, rather than months. However, these opportunities can provide cost-effective mechanisms for access to space for appropriate climate sensors and measurements, and should be considered.

Leveraging International Efforts

The committee recognizes the value of bilateral and multilateral cooperation among space agencies; notable examples include TRMM, Jason, and the planned GPM and JPS constellations.¹³ The committee also notes the value of various international planned activities and their potential contributions to better understanding of climate and its impacts, such as the European Sentinel-1, 2, and 3 missions that support the European Union and its Member States' operational services for Global Monitoring for Environmental Security (GMES).¹⁴ Other future satellite missions under ESA's Living Planet Programme—for example, GOCE, SMOS, ADM, and CryoSat-2—will support the GMES program and also provide valuable information for understanding and assessing Earth's climate system. The committee supports continued efforts to coordinate and strengthen international partnerships so as to ensure provision of key climate science measurements, and it recognizes the growing importance of such collaboration as budgets are increasingly stretched to accommodate the variety of stakeholder needs for Earth system data.¹⁵ However, large uncertainties are also associated with attempts to factor international partner missions into the timing of U.S. missions, including the obvious potential for program changes and continuing concerns about access to data, full participation in science teams, and difficulties related to restrictions associated with International Traffic in Arms Regulations (ITAR).¹⁶ This is especially true for emerging international space programs (e.g., in China).

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¹³In November 1998, NOAA entered into an agreement with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) to participate in the Initial Joint Polar-orbiting Satellite system (IJPS). The agreement calls for cooperation between NOAA and EUMETSAT to provide meteorological data for "morning" and "afternoon" orbits by complementing each other's polar satellite global coverage. Under this agreement NOAA will also provide some of the instruments on-board the EUMETSAT satellites (http://projects.osd.noaa. gov/IJPS/mission.htm). In June 2003, NOAA and EUMETSAT signed the Joint Transition Activities Agreement that will allow EUMETSAT and the United States continued access to environmental data collected by each other's satellites and calls for the parties to begin preparing for a future joint polar system (JPS) post 2020. The first MetOp satellite launched in late 2006.

¹⁴The GMES Space Component program includes the following instruments or sensing capabilities, which are grouped into "Sentinels": Sentinel-1, a C-band interferometric radar mission; Sentinel-2, a multispectral optical imaging mission; and Sentinel-3, a mission with wide-swath low-medium resolution optical and infrared radiometers and a radar altimeter package.

¹⁵On the role of international partners in future Earth observation missions, see also Chapter 3, "From Satellite Observations to Earth Information," in *Earth Science and Applications from Space* (NRC, 2007).

¹⁶Concerns about ITAR restrictions were discussed during the June 2007 workshop. A recent NRC report examines these issues in detail (NRC, 2008b).

SUMMARY OF PRIORITIES

While the committee found merit in all of the climate capabilities considered, it also recognized that absent sufficient resources, difficult choices would have to be made. Therefore, rather than recommending a wholesale restoration of all lost capabilities, the committee set out to provide a prioritized set of specific recommendations. Because the committee was not given any information concerning costs, relative or absolute, for any of the proposed mitigations, prioritization was based entirely on climate science merit. The committee notes, however, that had costs been provided, a more far-reaching set of recommendations might have been developed in which relative cost/benefit was taken into consideration.

As noted above, the committee prioritized the entire list of lost or diminished climate-related capabilities rather than limiting its recommendation to the demanifested sensors, as was done in the NASA-NOAA "remanifesting" study for the Office of Science and Technology Policy (OSTP). When interpreting the committee's findings, it is also important to recognize that the committee considered the importance of the duration of a measurement's record in the overall context of the measurement's value to climate science. This methodology appears to differ from that employed by the NASA-NOAA remanifesting study, which, by design, had as its primary objective to "ensure continuity of long-term records." The committee's approach is consistent with input received from the community as part of the June 2007 workshop.

Based on the results of the prioritization process, the committee found four natural groupings in its scoring prioritization (Figure 2.1), which are designated in descending order of priority as Tier 1 through Tier 4; a simplified version of these results is shown in Table 2.1. Within each group, the committee then considered each capability individually to provide recommended short- and long-term recovery strategies. Although the same nine questions were used to analyze the relative climate science impact of both GOES-R and NPOESS descopes in GEO and LEO orbits, respectively, sensors from the different programs were not prioritized head-to-head. However, it can be stated roughly that, considering climate science contributions alone, the recommendations regarding geostationary hyperspectral sounding compare to the Tier 2 LEO capability prioritization, and coastal waters imagery falls into Tier 4.

Prioritization of climate capabilities, although considered in the context of NPOESS and GOES-R programmatic changes, does not in all cases result in a recommendation for restoration of the originally planned sensors. Indeed, in the case of ALT, restoration of the original sensor to the NPOESS platform does not address the climate need for radar altimetry; yet provision of climate-quality radar altimetry is one of the highest-priority capabilities. Thus, as a recovery strategy the committee recommends a series of precision altimetry free flyers, rather than restoration of ALT to the NPOESS platforms.

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¹⁷Bryant Cramer, "Mitigation Approaches to Address Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals: Joint NASA-NOAA Study for OSTP (Phase II)," June 19, 2007, available at http://www7.nationalacademies.org/ssb/NPOESSWork-shop_Cramer_NRC_06_19_07_final.pdf and also reprinted in Appendix C of the June 2007 workshop report.

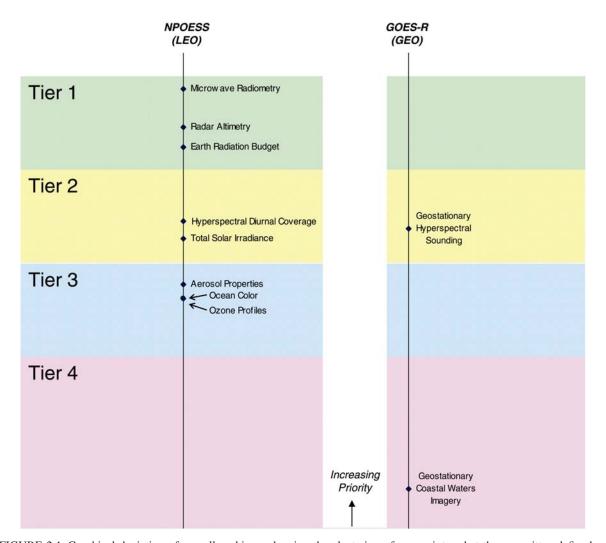


FIGURE 2.1 Graphical depiction of overall rankings, showing the clustering of scores into what the committee defined as Tiers 1-4, for recovery of both NPOESS (low Earth orbit) and GOES-R (geostationary Earth orbit) lost or degraded climate capabilities.

TABLE 2.1 Relative Prioritization for the Mitigation of Lost or Degraded Climate Capabilities

	Lost or Degraded Climate Capability in NPOESS Low Earth Orbit	Lost or Degraded Climate Capability in GOES-R Geostationary Earth Orbit	
Tier 1	Microwave Radiometry Radar Altimetry Earth Radiation Budget		
Γier 2	Hyperspectral Diurnal Coverage Total Solar Irradiance	Geostationary Hyperspectral Sounding	
Tier 3	Aerosol Properties Ocean Color Ozone Profiles		
Tier 4		Geostationary Coastal Waters Imagery	

Recommended Short-Term Recovery Strategy

In this chapter, the committee presents a summary of the analysis that informed its recommended prioritization.¹ As noted above, prior to the meeting, one or more committee members with the requisite expertise was assigned the task of preparing a detailed review of the issues associated with the descoping or demanifesting of a particular NPOESS or GOES-R measurement capability. In forming its judgments, the committee relied on the information in these presentations as well as the recommendations and detailed background information found in several recent NRC reports.² The text in this chapter provides highlights of the factors that informed the committee's ranking; however, it is not meant to be an exhaustive summary of the information considered by the committee.³

RATIONALE FOR PRIORITIZATION: NPOESS LOST CAPABILITIES

Microwave Radiometry

Related NPOESS Sensor	CMIS
Post-Nunn-McCurdy Status	"A reduced capability sensor" CMIS canceled; descoped MIS instrument to be included on C2 and later platforms
Climate Applications	Sea-surface temperature and wind, sea ice extent, snow cover, soil wetness, atmospheric moisture
Mitigation Priority	Tier 1

¹The process by which the committee performed its prioritization is discussed in Chapter 2; the priorities are based on an average of each member's numerical ranking of the importance of the lost or degraded climate capability, according to an unweighted average of responses to the nine questions shown in Chapter 2.

²See especially the report of the June 2007 workshop (NRC, 2008; reprinted in Appendix B) and Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (NRC, 2007); Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites; and Climate Data Records from Environmental Satellites: Interim Report (NRC, 2004).

³Some of the material in this chapter was revised and/or extended after the ranking process was completed. These changes improved the clarity and depth of the analyses in this chapter; they did not, however, alter the committee's findings shown here.

Highlights of Analysis

Satellite microwave (MW) radiometry has a 35-year heritage of providing highly accurate geophysical retrievals for Earth science. By viewing Earth over a broad spectral band ranging from 6 to 90 GHz, a large set of environmental parameters can be simultaneously estimated. The lower frequency channels penetrate the layers of cloud, giving an uninterrupted view of Earth's surface. MW surface measurements include sea-surface temperature and wind, sea ice extent, snow cover, and soil wetness. The higher frequencies provide information on atmospheric moisture in all of its various forms: vapor, cloud, rain, and ice.⁴

The alteration of the planet's hydrologic cycle due to global warming is one of the most (if not the most) critical issues associated with climate change, and satellite MW radiometry products are important inputs for the calculation of the planet's changing water and energy budget. MW radiometry provides direct measurement of precipitation over both land and ocean. Over the ocean, sea-surface temperature, wind speed, and water vapor are retrieved, all of which are needed for the computation of evaporation; there is also the potential to determine water vapor advection and storage, drivers for air-sea fluxes, and global ocean circulation and upwelling. Additional hydrologic parameters are sea ice extent, snow cover, and soil wetness, although the latter two are more qualitative measurements.

The importance of sea-surface temperature (SST) to climate research/science is hard to overstate. For example, SST is a key parameter in determining how the water and energy fluxes at the air-sea interface affect the hydrologic cycle and the surface radiation balance (e.g., Curry et al., 2004). The intensity, frequency, and location of hurricanes are in part determined by the availability of oceanic heat to sustain, encourage, or dissipate these storms. Climate oscillations such as the El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Pacific Decadal Oscillation (PDO) all have characteristic signatures that are visible in patterns of SST, precipitation, water vapor, cloud cover, and surface winds (scalar and vector). Because 6 GHz MW observations penetrate the clouds, are not affected by aerosols, and are only slightly affected by water vapor (an effect that is easily removed using higher frequency channels), the microwave radiometer has a distinct advantage over infrared sensors. The endemic cloud cover at high latitudes prevents monitoring of ocean temperatures by infrared radiometers, and microwave radiometers provide the only way to continually measure SST in these vital Arctic regions, which are now experiencing rapid climate change. Tropical convergence zones are also prime examples of persistently cloudy regions where SST detection by infrared sensors is problematic. However, the MW radiometer cannot provide the high spatial resolution or the near-coastal retrievals offered by the IR techniques. The two techniques are thus highly synergistic, and the combination of the MW radiometer with IR measurements provides the best means to accurately measure SST.

Microwave radiometers, specifically the Scanning Multi-channel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I), provided the first convincing evidence that the Arctic polar ice was depleting. The Arctic ice plays a critical role in global climate change by regulating ocean-atmosphere transfers of energy and water and helping control ocean surface salinity. Sea ice albedo feedbacks amplify climate impacts in the polar regions. Variables such as ice extent, concentration, and type are important for navigation as well as for marine habitat assessment. Satellite observations of September minimum sea ice show that sea ice extent has declined 8.6 percent +/- 2.9 percent per decade over the period 1979-2006 (Serreze et al., 2007). Snow cover in the Northern Hemisphere has also declined by 1.28 × 10⁶ km² over the period 1972-2006 (Déry and Brown, 2007). This decline in snow cover is significant because, compared with other land cover types, snow has a very high albedo and climate feedbacks are felt on local, regional, and even hemispheric scales.

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⁴Monitoring water vapor via its emission at 22.235 GHz, the MW radiometer provides the most accurate means to measure total columnar water vapor. In the absence of rain, the MW radiometer also provides the most accurate means to measure total columnar cloud water. By design (i.e., by including the 89 GHz channels), the MW radiometer can *detect* scattering from ice particles, the third phase of water. However, unlike the measurements of water vapor and liquid water, this detection is not a quantitative measurement.

⁵In the IPCC 4th Assessment it is stated that "continuous satellite measurements capture most of the Earth's seasonal snow cover on land, and reveal that Northern Hemisphere spring snow cover has declined by about 2 percent per decade since 1966, although there is little change in autumn or early winter. In many places, the spring decrease has occurred despite increases in precipitation" (IPCC, 2007, p. 18). Recent unpublished work concludes that snow cover in the Northern Hemisphere has been declining at a rate of about 3 to 5 percent per decade during spring and summer (Brodzik et al., 2006).

As has been demonstrated via WindSat, 6 microwave radiometers are capable of measuring vector winds (that is, both wind direction and speed) over the ocean by using polarimetric observations. Surface vector wind (SVW) controls the air-sea transfer of momentum and vorticity, and the surface wind speed modulates air-sea transfers of heat and fresh water. SVW and wind stress curl drive coastal and open-ocean upwelling processes affecting global primary production and oceanic mass transfers (e.g., cross-shelf transport and CO₂ uptake). As such, characterization and quantification of the role of the global ocean as a planetary heat and carbon sink depend critically on accurate representation of the global SVW. However, passive MW measurements of vector winds are not comparable in accuracy, coverage, or resolution to measurements from radar scatterometers such as the Sea Winds instrument on NASA's QuikSCAT. The differences are even more dramatic when comparing the capabilities of passive radiometers (e.g., WindSat and CMIS/MIS) with those of the advanced ocean vector winds scatterometer mission, known as the Extended Ocean Vector Winds Mission (XOVWM), which was recommended in the 2007 NRC Earth Science and Applications from Space decadal survey. XOVWM's ability to provide highly accurate wind vectors at a high spatial resolution (5 km) in the presence of rain and near coastlines (target value of 2.5 km) far exceeds what is achievable by passive radiometry. Thus, provision of climate quality ocean vector winds measurements requires consideration of mitigation options beyond the NPOESS passive microwave sounder.

Scatterometers are active spaceborne systems that emit directed microwave signals and detect corresponding backscatter to infer surface wind speed and direction over water surfaces. SVW retrievals from scatterometer observations have been used to demonstrate global surface wind kinetic energy content, vorticity, and divergence at spatial scales of about 25 km. SVW from scatterometer observations have a pronounced impact on the response of global ocean general circulation models (OGCMs) in terms of, for example, mass and heat transports, overturning circulations, and synoptic eddy field energy (Milliff et al., 1999). The spatial resolution and global coverage of SVW from scatterometer observations are commensurate with, and provide forcing for, the ocean synoptic-scale eddies (e.g., Spall, 2007) that transport heat, organize and sequester ocean ecosystems, and contribute significantly to the ocean general circulation (Hughes and Wilson, 2008). OGCMs are a critical component of the coupled climate model systems from which climate scenario calculations are obtained. The ocean role in climate scenarios gleaned from the coupled systems must be verified against ocean-only OGCM calculations driven by realistic SVWs.

The radar backscatter signal detected by scatterometers has other important climate implications as well. For example, reprocessing of the 1999 to 2005 QuikSCAT backscatter time series for sea ice classification produced a unique record that captured the diminishing Arctic multiyear and summer sea ice extent conditions leading to a record minimum in 2005. Drastic regional reduction and redistributions of the perennial ice in 2005 resulted in a net decrease in the total perennial ice extent of an area equivalent to the size of Texas (Nghiem et al., 2006).

The Conical-scanning Microwave Imager and Sounder (CMIS) instrument that was planned for NPOESS C1 and subsequent platforms was canceled as a result of the Nunn-McCurdy certification. A descoped sensor, designated as MIS (Microwave Imager and Sounder), is now planned to replace CMIS on NPOESS C2 and subsequent platforms. At its December 2007 meeting, the committee heard briefings by NPOESS officials on the status of the MIS procurement. At that time, formal specifications for MIS could not be disclosed; however, the committee was informed that the instrument would include core radiometry channels (10-89 GHz), soil moisture/sea surface temperature channels (6 GHz), and wind direction (10-37 GHz) polarimetric channels, while relying upon CrIS/ATMS to meet temperature and moisture sounding requirements that have been designated as key performance

⁶WindSat is a joint IPO/DOD/NASA risk reduction demonstration project intended to measure ocean surface wind speed and wind direction from space using a polarimetric radiometer. Launched in June 2003 by an Air Force Titan II rocket into an 830 km 98.7 degree orbit, it has exceeded its 3-year design life. See http://www.nrl.navy.mil/WindSat/index.php.

⁷The decadal survey recommendation for XOVWM was prompted in part by the recognition of the importance of data from scatterometers to climate research and prediction. See also Z. Jelenak, P.S. Chang, J. Sienkiewicz, R. Knabb (NOAA), and D. Chelton (Oregon State University), "Current and Future Needs and Solutions for Ocean Surface Vector Wind Measurements from Space," presentation to the committee, June 20, 2007, available at www7.nationalacademies.org/ssb/NPOESSWorkshop_NRC_Workshop_June07_zjelenak.pdf; Freilich and Vanhoff (2006), and Monaldo (2006). Also of interest regarding XOVWM versus QuikSCAT and WindSat are presentations given at the NOAA Operational Satellite SVW Winds Requirements Workshop on June 5-7, 2006; available at http://manati.orbit.nesdis.noaa.gov/SVW_nextgen/workshop_outline.html.

BOX 3.1 SUAG Priorities

- 1. Core Radiometry Channels (10-89 GHz)
- 2. Sounding Channels (50-60, 166 and 183 GHz)
- 3. Soil Moisture/Sea Surface Temperature (6 GHz)
- 4. Wind Direction (10-37 GHz polarimetric channels)
- 5. Upper Atmospheric Sounding (60-63 GHz)

SOURCE: Presentation to the committee, October 9, 2007. Available at http://www7.nationalacademies.org/ssb/NPOESS_mitigate_descope_presentation_Schneider_StGermain.pdf.

parameters (KPPs).⁸ This would be a deviation from the NPOESS Science User Advisory Group (SUAG)⁹ recommendations (see Box 3.1), which placed a clear emphasis on atmospheric temperature and moisture vertical profiles over polarimetric channels (SUAG priority 4). However, shortly before this report went to press, the committee learned that the first MIS, scheduled for launch on NPOESS C2, will, in fact, be procured with the desired sounding channels (SUAG priority 2).

The first MIS is planned for the C2 platform, which is currently scheduled for launch no earlier than 2016. For a variety of reasons, the committee believes future planning should include the significant likelihood for another slip in the schedule past 2016. Thus, the committee sees a very real risk of a substantial gap in the time series of microwave climate products. Currently, there are only two operational MW radiometers that have the spectral bands and spatial resolution necessary for adequate climate monitoring: AMSR-E on Aqua and WindSat on Coriolis. ¹⁰ Unfortunately, both of the sensors are already beyond their specified mission life, and it is extremely unlikely that either sensor will be in operation when the C2 platform is launched.

A follow-on, AMSR-2, is scheduled to fly on JAXA's GCOM-W platform, but not before 2012, and no follow-on is planned for WindSat. Furthermore, the GCOM-W launch schedule may slip, and premature spacecraft failures have occurred in the previous two JAXA Earth observation missions. In view of this, relying solely on AMSR-2 to continue the MW climate time series carries considerable risk. Another MW radiometer, GMI, 11 is scheduled for launch in 2013, but it does not have 6 GHz channels or the high spatial resolution of AMSR and WindSat. In addition, GMI will not view the high latitudes due to its 65° inclination orbit. The only other U.S. MW radiometers (other than sounders) that are scheduled for launch are part of the SSM/IS series. However, the SSM/IS lacks both the spatial resolution and spectral range required for adequate climate monitoring.

Should AMSR-2 be delayed or experience an early failure, a significant data gap of many years will occur. In the committee's view, this would be devastating to climate monitoring of SST and the hydrologic cycle. Given the importance of the MW radiometer for climate monitoring, the committee found cancellation of CMIS on the

⁸The DOD and DOC would consider the NPOESS system to have a major flaw if it did not meet its key performance parameters (KPPs) as outlined in the Integrated Operational Requirements Document (IORD) II (December 10, 2001). A KPP is defined as a measurable capability or characteristic a system must deliver or display when declared operational. Any system or program not meeting a KPP is a candidate for termination. See "The Future of NPOESS: Results of the Nunn-McCurdy Review of NOAA's Weather Satellite Program," Hearing before the Committee on Science, House of Representatives, One Hundred Ninth Congress, Second Session, June 8, 2006, available at http://bulk.resource.org/gpo.gov/hearings/109h/27970.pdf.

⁹The SUAG represents the primary U.S. government users of NPOESS data. See Memorandum of Agreement Between the Department of Commerce, Department of Defense, and National Aeronautics and Space Administration for the National Polar-Orbiting Operational Environmental Satellite System (NPOESS). Available at http://www.hq.nasa.gov/pao/History/presrep95/f1.htm.

¹⁰Both of these sensors have the C-band channels (i.e., 6 GHz) necessary for global SST and surface wetness retrievals and a large enough antenna (i.e., 2 m) to provide adequate spatial resolution.

¹¹The GPM Microwave Imager (GMI) is NASA's key contribution to the U.S.-Japanese Global Precipitation Mission, which is scheduled for launch in 2013.

NPOESS C1 platform both puzzling and ill advised. CMIS represented the state of the art in satellite MW radiometers and was intended to continue, with a higher degree of accuracy and resolution, the time series of many fundamental climate variables. The ability of CMIS to measure surface characteristics through clouds and provide direct measurements of the changing hydrologic cycle made it a unique and essential sensor for climate. In the committee's view, the cancellation of CMIS and the decision to forgo the inclusion of its replacement, MIS, on NPOESS C1, jeopardizes a national commitment to the enhancement of scientific understanding of global climate change. 12

Finding: In view of its capability for monitoring the hydrologic cycle, SST, and sea ice, the committee ranks provision of microwave radiometry as its highest priority. The committee finds that AMSR-2 by itself is not sufficient to avoid a data gap and recommends that a mitigation strategy be formulated to supplement AMSR-2 with another MW radiometer of similar design. This ranking stems largely from it receiving the highest score for its use in climate data records (question 1), role in reducing uncertainty (question 2), use in reanalysis (question 4), contributions to understanding the climate system (question 8), and use in other disciplines (question 9).

Preferred Recovery Strategy and Other Mitigation Options

The preferred mitigation is to build a new MW radiometer specifically designed for climate monitoring, and fly it on either a free flyer or a flight of opportunity. Formation flight with NPP or NPOESS C1 is highly desirable, as it would enable provision of near-simultaneous IR measurements from CrIS/ATMS to complement the MW observations. The radiometer could be considerably simpler than MIS in that it does not need to have the polarimetric channels required for recovery of vector winds, nor the sounding channels; a basic AMSR-type design would be sufficient.

Additional mitigation options include:

- Adding C-band channels to NASA's GMI instrument, and enlarging its antenna. ¹³ Although GMI's orbit inclination of 65° is not ideal for ocean monitoring, it is sufficient to view most ocean areas.
- Modifying the MW radiometer that is planned for the advanced scatterometer mission XOVWM, which has a recommended launch date of around 2012, to include at least 3 or 4 frequencies, one being C-band, as well as an improved on-board calibration system. The synergy of a scatterometer and a MW radiometer on the same platform is significant and would improve both the scatterometer and radiometer retrievals.

There are significant costs and schedule impacts associated with each of these options. Accordingly, the committee makes the following recommendations:

- 1. NASA and NOAA should initiate a study as soon as practicable to address continuity of microwave radiometry and to determine a cost-effective approach to supplement the AMSR-2, carried on the Japanese spacecraft GCOM-W, with another microwave radiometer of similar design. The agencies should also consider the feasibility of manifesting a microwave radiometer on a flight of opportunity or free flyer to cover the microwave radiometry gap anticipated with a delay in accommodation of MIS until NPOESS C2.
- 2. The agencies should provide funding for U.S. participation in an AMSR-2 science team to take full advantage of this upcoming microwave radiometer mission.
- 3. The NPOESS Integrated Program Office should continue with its plans to restore a microwave sounder to NPOESS C2 and subsequent platforms, with an emphasis on SUAG priorities 1 through 3 (core radiometry, sounding channels, and soil moisture/sea surface temperature).

¹²U.S. Climate Change Science Program, "Strategic Plan for the Climate Change Science Program," available at http://www.climatescience.gov/.

¹³Without the C-band channels, accurate SST measurements cannot be obtained for SST less than 12°C. This excludes a large portion of the world's oceans.

Scatterometry is the clearly preferred approach for obtaining ocean vector winds, and the committee urges the agencies to hasten development of operational ocean vector wind capability to meet both climate and weather forecasting needs. Considering the advanced capabilities of XOVWM as compared to the QuikSCAT-type scatterometer (particularly with respect to measurement in storms and hurricanes), the preferred option is to put XOVWM on the fast track and launch as soon as possible, as opposed to launching another QuikSCAT. Due to fundamental limitations of the passive MW approach for measuring vector winds, the committee does not view restoration of polarimetry to MIS as adequate to meet the data needs of climate researchers studying connections between seasurface vector winds and climate. Accordingly, the committee offers the following recommendation:

4. NASA and NOAA should devise and implement a long-term strategy to provide sea-surface wind vector measurements. The committee finds important limitations in the planned reliance on a polarimetric radiometer for this measurement; instead, the preferred strategy is timely development and launch of the next-generation advanced scatterometer mission, that is, the Extended Ocean Vector Winds Mission (XOVWM) recommended in the 2007 NRC decadal survey *Earth Science and Applications from Space*.

Radar Altimetry

Related NPOESS Sensor A

ALT

Post-Nunn-McCurdy Status

"A demanifested sensor"

Climate Applications

Sea level height, regional ocean currents, basin-scale ocean circulation

Mitigation Priority

Tier 1

Highlights of Analysis

Sea level is a fundamental indicator of changes in Earth's climate. Sea level measurements provide insight into ENSO processes (e.g., onset, strength, planetary waves) and other climate oscillations (e.g., PDO) that are important for understanding the impacts of short-term variations in climate, and are key to observing changes in ocean circulation. Sea level changes, in response to heat absorption by the oceans (via thermal expansion) as well as the contribution of melting ice from glaciers and the polar ice caps, will have profound socioeconomic impacts on coastal populations around the world. Thus, sea level is a critically important variable to monitor as Earth warms; it is needed to both predict future impacts and inform mitigation strategies.

Prior to the satellite era, tide gauge measurements were the primary means of monitoring sea level change. However, their poor spatial distribution and ambiguous nature (e.g., vertical land motion can cause erroneous signals that mimic the effects of climate change at some sites) made them of limited use for climate studies. With the launch of TOPEX/Poseidon (T/P) in 1992, satellite altimeter measurements with sufficient accuracy to monitor sea level change became available (Cazenave and Nerem, 2004). TOPEX/Poseidon was the first mission with sufficient measurement accuracy (corrections for ionosphere and troposphere delays), orbit accuracy (three separate precision orbit determination systems), and orbit sampling characteristics (orbit does not alias tidal variations to "climate-like" frequencies) that monitoring small (mm/year) changes in sea level was possible. Jason-1, launched at the end of 2001, has continued the T/P measurements in the same orbit/ground track, including a critical 6-month intercalibration phase with T/P. The TOPEX/Poseidon and Jason-1 missions have resulted in a continuous 15-year time series of precisely calibrated sea level measurements (Figure 3.1). These measurements have allowed satellite monitoring of global mean sea level change (Figure 3.2), which has risen at an average rate of ~3.5 mm/year during the altimeter era (Figure 3.3), nearly double the rate observed by tide gauges over the

¹⁴While other satellite altimeter measurements had previously flown, they either did not have the instrument or orbit determination precision (Seasat, Geosat), and/or they flew in Sun-synchronous orbits (e.g., ERS, Envisat) that are undesirable for climate research and applications.

¹⁵Overlap between the missions is critical for assessing instrument performance, differences between instruments, and other factors that vary from one mission to the next.

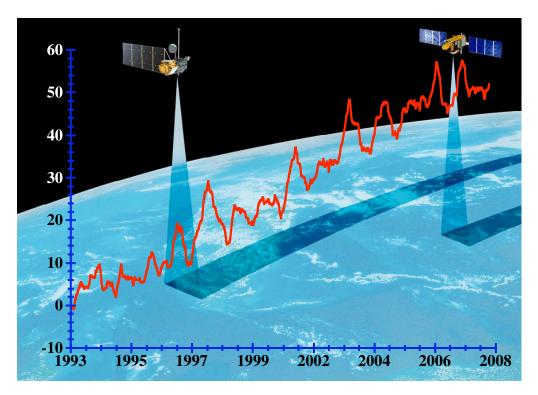


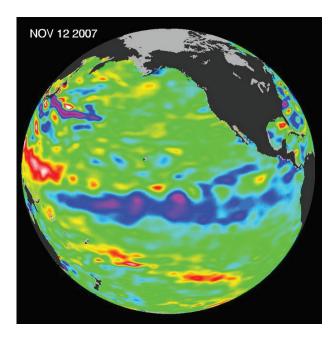
FIGURE 3.1 Global mean sea level variations (mm) from the TOPEX/Poseidon and Jason-1 missions. SOURCE: Courtesy of Centre National d'Etudes Spatiales/D. Ducros.

last century (Leuliette et al., 2004; Beckley et al., 2007). Another powerful aspect of satellite altimetry is that it provides maps of the spatial variability of the sea level rise signal, which is valuable for the identification of sea level "fingerprints" associated with climate change (Mitrovica et al., 2001).

Jason-2, also called the Ocean Surface Topography Mission (OSTM)/Jason-2, carrying similar payload to Jason-1 with improved technology, is scheduled for launch in June 2008, ¹⁶ and will hopefully enjoy a similar intercalibration period with Jason-1. Discussions for a Jason-3 mission are currently under way between NOAA and EUMETSAT as part of a transition of satellite altimetry to "operational" status, but the mission is still very uncertain, and a gap after Jason-2 is a very real possibility. Researchers hope to avoid a gap in this 15-year satellite record as measurements from tide gauges and Sun-synchronous satellite measurements would not be sufficient to accurately determine the bias between the two time series on either side of the gap. A measurement gap presents two problems: (1) scientists are unable to monitor sea level changes due to sudden shifts in the climate system or natural events (e.g., ENSO events, volcanic eruptions, etc.) occurring during the gap, and (2) a gap in the record will make it more difficult to determine if the rate of sea level rise is accelerating—ultimately requiring an even longer time series before this determination can be made.

Sea level measurements from satellite altimetry benefit a broad array of climate science disciplines including ocean science, cryospheric science, hydrology, and climate modeling applications because sea level change is a barometer for changes in the global water cycle. While measurements from satellite gravity missions such as GRACE provide direct measurement of hydrologic and cryospheric contributions to sea level change, satellite altimeter measurements measure the total sea level change, including ocean thermal expansion not observed by GRACE, and thus are best suited for measuring the spatial variability of the sea level change and predicting the

¹⁶Note added in proof: The present report was completed before the successful launch of OSTM/Jason-2 on June 20, 2008.



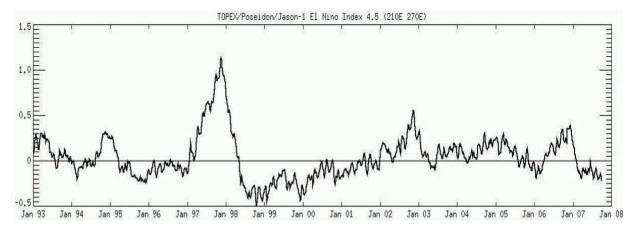


FIGURE 3.2 Sea level (from Jason-1 and TOPEX/Poseidon) in the Pacific averaged over 5°S-5°N, 210°-270°E (bottom) and as a change map (Jason-1 data only, top). SOURCE: Courtesy of L. Fu/NASA/JPL.

socioeconomic impacts on coastal areas. Sea level measurements were used prominently in the most recent IPCC assessment, and promise to be an even more integral part of future assessments because of their direct relation to changes in ocean heat content and land ice melt, as well as their use in assessing global climate models through hindcasts (Rahmstorf et al., 2007). The predictions of future sea level change were one of the most contentious aspects of the IPCC 4th assessment and thus satellite altimetry will be an important tool for scientists preparing future assessments.

Sea level measurements are also used extensively in ocean reanalysis efforts (e.g., ECCO, SODA) and short-term climate predictions.¹⁷ However, sea level measurements have not been extensively used in long-term climate

¹⁷ECCO is the acronym for Estimating the Circulation and Climate of the Ocean; SODA is the acronym for Simple Ocean Data Assimilation.

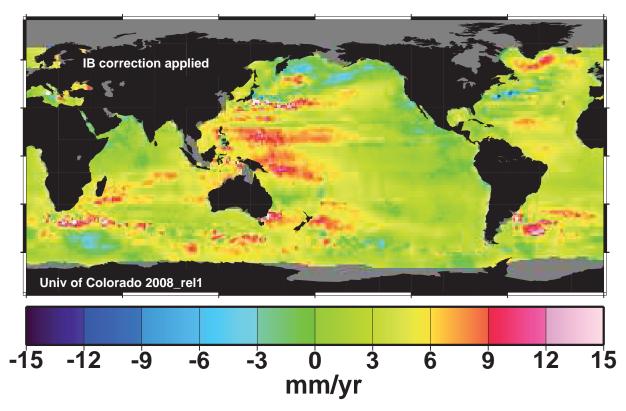


FIGURE 3.3 Trends (mm/year) in sea level change over 1993-2007 from TOPEX/Poseidon and Jason-1 altimeter measurements. SOURCE: Courtesy of Colorado Center for Astrodynamics Research, University of Colorado at Boulder. For more information, see http:// sealevel.colorado.edu and Leuliette, E.W., R.S. Nerem, and G.T. Mitchum, Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change, *Marine Geodesy* 27(1-2):79-94, 2004.

projections because the current and future response of the ice sheets is poorly understood. Nevertheless, sea level measurements are an important tool for testing climate model projections.

The committee notes that satellite altimetry is a very mature measurement technique. While there is still active research on improvements in the measurement processing, especially for the demanding applications of climate science, the measurement system as a whole is very well understood. The ALT instrument, demanifested from NPOESS following Nunn-McCurdy certification, is a mature state-of-the-art sea level measurement system with a well-understood long-term calibration scheme (tide gauges). However, the NPOESS Sun-synchronous orbit is incompatible with climate science needs for precision radar altimetry. Satellite altimetry also requires precision orbit determination, which is accomplished via dedicated precision satellite geodetic observations (e.g., GPS, DORIS, SLR). However, the precision of these techniques can be compromised as a result of their placement on large satellites that have multiple instruments and a variety of accommodation requirements. For these reasons, the originally intended NPOESS altimetry capability was undesirable for climate studies.

In summary, the committee recognizes the importance of an uninterrupted record of sea level change measurements for climate science research and policy making, and thus strongly advocates that the record of sea level change from these missions be continued. However, the originally intended NPOESS altimetry capability was ill-suited for climate studies, primarily because the NPOESS Sun-synchronous orbit was problematic for separating tidally driven versus climate-related sea level changes. Thus, restoration of the ALT sensor to NPOESS would require justification via applications outside climate science.

Finding: Overall, radar altimetry ranks in the first tier of climate priorities. Radar altimetry ranked highly in terms of contribution to climate data records (question 1), its role in climate prediction (question 3), measurement maturity (question 5), uniqueness (question 6), and use in reanalysis (question 7).

Preferred Recovery Strategy and Other Mitigation Options

The committee's preferred recovery strategy for radar altimetry climate needs is to fly a Jason-3 mission and subsequent series of precision altimetry free flyers in order to continue the climate data record that was initiated by TOPEX/Poseidon and Jason-1, and is to be continued in the near term by OSTM/Jason-2. While flying Jason-3 in the same orbit (66° inclination, 1,336 km altitude) as the earlier satellites is preferable, proposals to increase the inclination (improving the latitudinal coverage) and lower the altitude (reducing spacecraft cost) are acceptable, particularly if there is overlap with Jason-2 (allowing the intercalibration of the measurements from the two orbits) and if tidal aliasing is properly considered in the orbit selection. Changes to the near 10-day repeat period of the current orbit are not a major concern for climate studies.

The committee is also aware of efforts to develop a "wide-swath" altimeter mission for hydrologic and oceanic applications recommended for launch in the 2013-2016 time frame by the decadal survey. While the committee supports this initiative, the utility of this novel measurement approach for sustained climate monitoring will not be fully known until the measurements have been collected and analyzed, and thus it is not considered a substitute for a Jason-3 mission.

There are no apparent viable options should a Jason-3 mission fail to materialize. While other altimeter missions are planned in the European community, they employ Sun-synchronous orbits that are not suitable for climate studies. Proposed alternatives to Jason-3 must properly consider requirements for orbit selection, measurement accuracy, calibration, and precision orbit determination, while relying upon mature, low-risk technology.

Recommendation: A precision altimetry follow-on mission to OSTM/Jason-2 (i.e., Jason-3) should be developed and launched in a time frame to ensure the necessary mission overlap. The agencies' long-term plan should include a series of precision altimetry free flyers in non-Sun-synchronous orbit designed to provide for climate-quality measurements of sea level.

Earth Radiation Budget

Related NPOESS Sensor	ERBS
Post-Nunn-McCurdy Status	"A demanifested sensor"
Climate Applications	Earth radiation budget at the top and bottom of the atmosphere
Mitigation Priority	Tier 1

Highlights of Analysis

Measurements of regional and global radiation balance date to the 1960s when the first satellites were launched, and they were further enabled with the launch in the late 1970s of Nimbus 6 and 7, which carried the first true broadband radiation scanning sensors. NASA's Earth Radiation Budget Experiment provided the second generation of true broadband data and the first scanners with sufficient spatial resolution to separate clear-sky scenes and allow for the direct observation of cloud radiative effect (Figure 3.4). The third-generation instrument, CERES (Clouds and the Earth's Radiant Energy System), is included on the TRMM (1997-), Terra (1999-), and Aqua (2002-) missions. Calibration and data analysis accuracy have improved with each generation.

Earth radiation budget products currently include both solar-reflected and Earth-emitted radiation from the top of the atmosphere (TOA) to Earth's surface. Through synergies with simultaneous measurements by other EOS instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS), it is possible to relate cloud

(a)



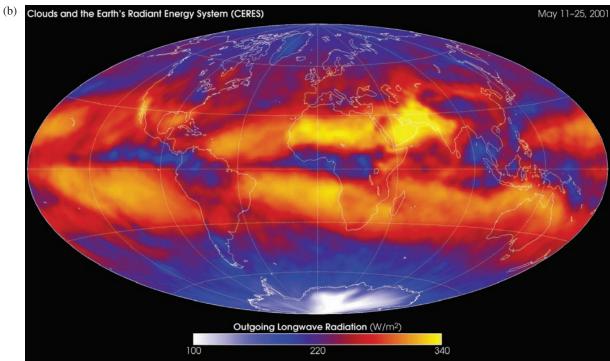


FIGURE 3.4 (a) Installation of flight multilayer insulation on CERES Flight Models 1 and 2 at the TRW clean room facility after completion of calibration in preparation for shipment to Vandenberg for integration on Terra. SOURCE: Courtesy of NASA, available at http://asd-www.larc.nasa.gov/ceres/terra/pics.html. (b) Terra/CERES View of Earth. SOURCE: Courtesy of NASA/Goddard Space Flight Center Scientific Visualization Studio, available at http://visibleearth.nasa.gov/view_rec. php?id=11907.

properties to the radiation budget and determine both climate forcing and climate response. Analyses of CERES data are leading to a better understanding of the role of clouds and the energy cycle in global climate change, and to improved assessments of the change in Earth's climate as a function of time.

Unscrambling climate signal cause-and-effect requires a complete parameter set at climate accuracy. Earth radiation budget measurement utilization requires multispectral imagery data, which are currently supplied by MODIS; in the NPOESS time frame, these data will be supplied by VIIRS. CERES analyses routinely merge TOA radiation data with cloud, aerosol, snow, and ice property retrievals from MODIS, microwave sea-ice coverage, aerosol assimilation data, 4-D assimilation of weather data, and 3-hour geostationary satellite data.

The largest uncertainty in global climate sensitivity over the next century is cloud feedback (especially for low clouds). IPCC coupled atmosphere-ocean models show that cloud feedback is linearly related to top-of-atmosphere net cloud radiative effect, and climate sensitivity is linearly related to cloud feedback (Soden and Held, 2006). CERES will observe decadal changes in net cloud radiative effect that will reduce the uncertainty in cloud feedback and therefore climate sensitivity. To achieve this objective, the minimum calibration goal for decadal change observations of TOA radiation is 0.35 percent per decade for SW and 0.6 percent per decade for LW (95 percent confidence). These goals cannot be achieved if there is a gap in the TOA radiation record, as they are a factor of 5 more stringent than the current state of the art for absolute accuracy in broadband radiometers in the SW, and a factor of 2 more stringent in the LW. Thus, TOA radiation measurements must be overlapping from one mission to the next; a gap of any length will restart the climate record at zero.

Earth radiation budget measurements have played an important role in climate prediction and projections. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4)¹⁸ model results of the change in global mean surface air temperature and cloud radiative effect (CRE) under the A1b emission scenario suggest that monitoring the future evolution of CRE gives an earlier indication of what climate sensitivity trajectory we are on than does monitoring of the global mean temperature (Figure 3.5). For example, by 2050 an observational record of CRE with a stability of 0.5 Wm⁻² per 50 years would eliminate approximately 50 percent of the models as being inconsistent with the observed record. Therefore, based on these results, Global Circulation Models (GCMs) suggest that ERB measurements likely provide a better metric than surface air temperature for predicting the actual climate sensitivity trajectory.

Broadband radiation budget data for ERBS and CERES were used in the most recent IPCC 2007 observations chapter to determine the interannual variability in ocean heat storage (global net radiation, e.g., Wong et al., 2006), to counter spurious climate signals in global planetary albedo such as those from the astronomical Earthshine observations (Wielicki et al., 2005), and to put in global energy perspective inferences of "global dimming" from surface broadband radiometers. The ERBS data also provided observations of decadal variations of tropical SW, LW, and net fluxes. More recently, CERES data were used to investigate a 2006 claim of ocean cooling from recent Argo data. This erroneous claim resulted from in situ biases between the old Expendable Bathythermograph (XBT) and new Argo in situ data (Willis et al., 2007). CERES data are also being used as the most accurate reference data for the WCRP GEWEX Radiative Flux Assessment, an international effort under way by over 50 international researchers evaluating both surface and TOA fluxes, their accuracy, and their ability to resolve decadal change in the climate system.

Finding: Sustaining the Earth radiation budget climate measurement record into the future ranked in the first tier of climate priorities. The Earth radiation budget measurement record ranked higher in the area of measurement maturity (question 5) than any other climate capability considered by the committee. It also ranked among the highest (second or third place) in the areas of extent the data are used in monitoring and providing a historical record of the global climate, extent this measurement is important in reducing "uncertainty," extent the data are used by the IPCC and the CCSP, and the measurement's role in contributing to an overall improved understanding of the climate system (questions 1, 2, 7, and 8).

¹⁸The three Working Groups' full reports and the Synthesis Report, the final part of the Fourth Assessment Report (AR4), are available online at http://www.ipcc.ch.

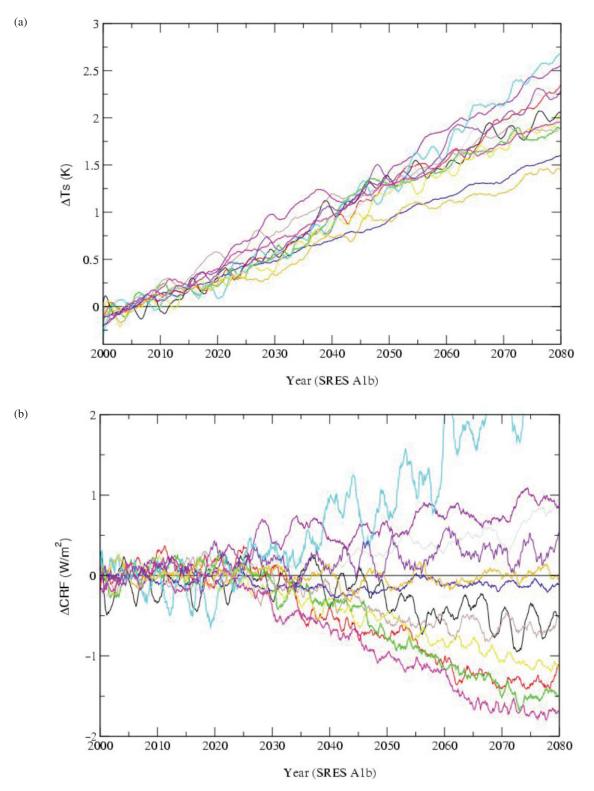


FIGURE 3.5 Change in global (a) surface air temperature and (b) cloud radiative forcing between 2000 and 2080 for IPCC AR4 GCM simulations (5-year running means). SOURCE: Courtesy of B. Soden, NOAA.

Preferred Recovery Strategy and Other Mitigation Options

The preferred recovery strategy is consistent with the recommendations of the decadal survey and June 2007 workshop report. Specifically, the agencies should (1) fly the CERES FM-5 on NPP, even if it causes a modest delay to the NPP launch date, ¹⁹ and (2) develop an Earth radiation budget instrument (series) to follow CERES FM-5 to fly in at least one Sun-synchronous orbit and continue and extend the rich Earth radiation budget long-term measurement record.²⁰

Due to ancillary data requirements, the CERES or ERBS-like instrument should either fly on the same platform as a VIIRS (or equivalent) imager or in formation (within 3 to 6 minutes) with the NPOESS VIIRS imager in the 1:30 LT orbit. The decadal survey's Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission could fundamentally change this dynamic, but it now appears unlikely to launch before 2013. CLARREO's nadir track spectrometer will acquire data traceable to SI (Systeme Internationale) standards across the full solar and IR broadband spectra at decadal change accuracy; these data could then be used to provide calibration transfer across short gaps in the CERES broadband record (NRC, 2007, pp. 93-95). CERES-like full-swath broadband data will still be required for space/time sampling of global change, but short gaps in the measurement record could then be of less consequence.

Recommendation: To minimize the risk of a potential data gap, the committee reiterates the recommendation of the 2007 *Earth Science and Applications from Space* decadal survey to manifest the CERES FM-5 on NPP.²¹ The agencies should further develop an ERB instrument series and provide for subsequent flights on Sun-synchronous platforms to continue the Earth radiation budget long-term record.

Hyperspectral Diurnal Coverage

Related NPOESS Sensor

CrIS/ATMS

Post-Nunn-McCurdy Status

"A reduced coverage sensor"

Climate Applications

Vertical temperature and moisture profiles, outgoing longwave radiation, greenhouse gas amounts, cloud properties, precipitation

Mitigation Priority

Tier 2

Highlights of Analysis

Understanding the diurnal variation of climate-relevant parameters and processes is essential for the improvement of the underlying physics of climate models, which must sufficiently capture the physics of short-time-scale processes to enable accurate predictions over long time periods.²² Greater sampling of the diurnal variability of

¹⁹The committee was informed NPP could launch no earlier than 14 months after delivery of the final instrument. As this report was being prepared, NOAA announced a delay in delivery of the VIIRS instrument to NPP (now anticipated for 1Q09) which would cause a launch delay. Restoration of CERES FM-5 to NPP should not require further launch delay.

²⁰The committee was informed that there are sufficient spare parts to assemble a CERES FM-6 for flight on C1, which might be leveraged as a potential cost savings option.

²¹This view was also expressed by many of the participants at the June 2007 workshop; it is also endorsed in the ongoing NASA-NOAA study. See Appendix B.

²²Undersampled diurnal variability introduces a bias into the time-mean behavior derived from observations, impacting the degree to which the global structure and evolution of a climate-relevant property can be reconstructed, particularly for the small-scale behaviors inherent to distributions of water vapor and cloud cover (Salby and Callaghan, 1997). Diurnal variations cannot be determined from a single polar-orbiting platform, as diurnal variability is indistinguishable from the time-mean. However, systematic error can be reduced by the use of measurements from multiple platforms in polar orbit, or through the improved temporal coverage obtained in geostationary orbit.

The change of diurnal cycle of the surface air temperature implies the existence of a substantial climate forcing located in continental regions. Karl et al. (1993) indicated that diurnal cycle changes non-symmetrically: averaged minimum temperature over 50 percent of Northern

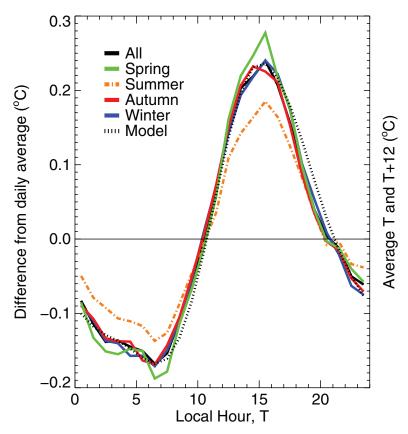


FIGURE 3.6 Diurnal cycle of sea surface temperature. SOURCE: J.J. Kennedy, P. Brohan, and S.F.B. Tett, A global climatology of the diurnal variations in sea-surface temperature and implications for MSU temperature trends, *Geophys. Res. Lett.* 34: L05712, doi:10.1029/2006GL028920. Copyright 2007 American Geophysical Union.

key parameters for climate-relevant processes (e.g., clouds, surface temperature, sea surface temperature, and humidity) will allow for improved simulation of important climate processes.

Improved diurnal coverage is also needed to accurately interpret long-term climate trends. For example, changes in global sea surface temperature due to warming trends are on the order of 0.1 K per decade (Wentz and Schabel, 2004). Seasonal as well as diurnal variability must be removed from these trends in order to make an accurate observation of the warming trends. Long-term observations allow for seasonal variability to be accommodated;²³ however, since all of these sounders are in a well-maintained Sun-synchronous polar orbit, each satellite only samples the diurnal cycle at two points. Any changes in the diurnal cycle can complicate the detection of small warming trends over time (Anderson et al., 2004). Figure 3.6 shows the diurnal cycle for SST, overlaid with the location of the AIRS, IASI, and CrIS observation locations (Kennedy et al., 2007). Quantification of the increased uncertainty introduced by the loss of CrIS in the NPOESS 05:30 terminator orbit has not been performed; however, as indicated by the figure, this time is well suited to fitting the diurnal cycle and significantly reducing

Hemisphere land in 1951-1990 increased by 0.85°C, while average maximum temperature increased only by 0.28°C. Observed variations of diurnal cycle allow the inference of fundamental information on the nature and location of main climate forcings (Hansen et al., 1995). The diurnal cycle of liquid water and cloud cover must also be included in the Earth's radiative budget (Bergman and Salby, 1997). Diurnal cycle amplitudes are a considerable fraction of the mean (15-35 percent), especially for low clouds, and vary geographically (Wood et al., 2002).

²³Seasonal fluctuations can be accommodated by the sounders through long-term observations. AIRS (aboard NASA's Aqua spacecraft) has thus far achieved over 5 years of observations, and IASI (aboard MetOp) is entering its second year. The NPOESS CrIS is planned to be operational for the next two decades.

uncertainty associated with its potential changes over time. The 05:30 orbit is particularly interesting, as it occurs at a transition point in the diurnal cycle from nighttime to daytime that may in some locations be highly sensitive to climate variability.

Prior to the NPOESS and GOES-R descopes, unprecedented diurnal hyperspectral coverage was anticipated from CrIS (on NPOESS) and HES (on GOES-R); however, after both programs were descoped, the anticipated improvements were essentially lost. Restoring CrIS/ATMS to the NPOESS C2 and C4 platforms would allow for soundings at approximately 4-hour intervals over the United States and coastal waters for severe weather applications rather than the up to 8-hour gap currently associated with the post-Nunn-McCurdy NPOESS architecture.²⁴

In addition to the climate value of additional hyperspectral diurnal coverage, there is an important risk mitigation aspect associated with restoration of CrIS/ATMS to the C2 and C4 platforms. Current MIS specifications imply reliance upon CrIS/ATMS to meet temperature and moisture sounding KPP requirements. However, CrIS/ATMS is not currently manifested on C2 or C4; therefore, soundings will not be provided in the 05:30 orbit. Pre-Nunn-McCurdy certification, KPP redundancy was assured, as VIIRS, CrIS, and ATMS were in both the 05:30 and 13:30 orbits, with VIIRS and MetOp (carrying AVHRR, IASI, and AMSU) in the 09:30 orbit. In such a configuration, single points of failure in any portion of the system still allowed for KPPs to be met. Post-Nunn-McCurdy certification, however, plans for an NPOESS with VIIRS in the 09:30 orbit were terminated and CrIS and ATMS were removed from the NPOESS satellite in the 05:30 orbit, thus negating redundancy for KPPs while at the same time placing the NPOESS system in jeopardy of loss in continuity of services. An unsuccessful launch of C1, or the premature failure within the C1 sounder system, would result in unmet KPPs.²⁵

Finding: Hyperspectral diurnal coverage ranked in the second tier of climate priorities for recovery. It scored highly in terms of contribution to a climate record (question 1) and measurement maturity (question 5).

Preferred Recovery Strategy and Other Mitigation Options

The preferred recovery strategy is to remanifest CrIS/ATMS on the NPOESS C2 and C4 platforms; thus, all NPOESS spacecraft would have as a minimum instrument configuration a VIIRS, a CrIS, and an ATMS. Remanifesting the sounder system on the C2 and C4 platforms would increase hyperspectral diurnal coverage to improve climate process understanding and reduce the risk of gaps in continuity of services by allowing C2 or C4 to be launched into the afternoon orbit if necessary to replace a C1 or C3 satellite. An ancillary benefit is the valuable additional data that would be available to support weather forecasting.

Recommendation: The CrIS/ATMS instrument suite should be restored to the 05:30 NPOESS orbit to provide improved hyperspectral diurnal coverage and support atmospheric moisture and temperature vertical profile key performance parameters.

Solar Irradiance

Related NPOESS Sensor

TSIS

Post-Nunn-McCurdy Status

44

"A demanifested sensor"

Climate Applications

Total solar irradiance, spectral solar irradiance

Mitigation Priority

Tier 2

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²⁴Post-Nunn-McCurdy, soundings are limited to the 01:30 NPOESS C1 orbit and 09:30 MetOp orbit. Considering both ascending and descending passes, there are alternating 4- and 8-hour intervals between measurements (i.e., 4 hours between the descending passes of C1 and MetOp, and then an 8-hour gap until the C1 ascending pass).

²⁵Note that the C2 satellite as currently configured has no CrIS or ATMS sounder capability and thus would not be an effective replacement for C1.

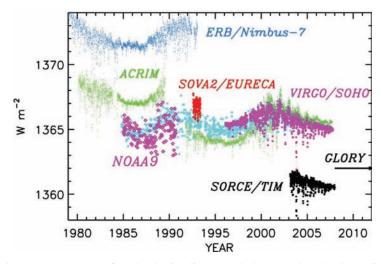


FIGURE 3.7 Compared are measurements of total solar irradiance made by space-based solar radiometers since November 1978. The TIM on Glory is planned for overlap with TIM on SORCE. The demanifest of the TSIS sensor on NPOESS means that the total solar irradiance record will terminate at the end of the Glory mission. SOURCE: Courtesy of Judith L. Lean, Naval Research Laboratory.

Highlights of Analysis

Solar irradiance variability is the only external forcing of the climate system. Since atmospheric interference precludes its measurement with sufficient accuracy and precision from Earth's surface, a space-based record is essential for specifying solar forcing of climate. Reliable knowledge of solar forcing is crucial because of its potential to either mitigate or exacerbate anthropogenic warming.

The current record of *total* solar irradiance extends uninterrupted since 1978 (Figure 3.7) and, although one of the longest continuous space-based climate records, covers less than three solar activity cycles. Composite 28-year time series (Fröhlich and Lean, 2004; see Figure 3.8) are constructed by accounting for differences in the uncertainties (absolute calibration) and repeatability (precision) of observations made by individual solar radiometers on many spacecraft.²⁶ An uninterrupted irradiance record that extends over many (not just a few) solar activity cycles with sufficient precision to resolve long-term solar changes that may manifest from one activity cycle minimum to the next is needed to understand the Sun's role in climate change. The magnitude of long-term solar irradiance changes is highly uncertain because the observational record is, thus far, too short to reliably detect possible centennial-scale variations that may underlie the 11-year activity cycle. *The committee notes the unique importance of a reliable, uninterrupted, long-term solar irradiance record for guiding policy by constraining external climate forcing to plausible limits.*

While the magnitude of solar forcing is expected to be considerably smaller than projected anthropogenic forcing in the next century (IPCC, 2007), empirical analysis of both recent and paleoclimate data caution that climate system responses to solar forcing are by no means properly understood, and may involve a variety of indirect processes and natural climate oscillations. Because of the uncertainty regarding both long-term solar forcing and climate responses, the IPCC's conclusions are not universally accepted; in fact, claims of significant solar-induced effects on climate are often reported in the public press as an alternative cause to global warming.

Recent debate about the Sun's role in global warming from 1980 to 2000 illustrates the type of ambiguity that can ensue when reliable climate-quality data are not available. During the period from about 1989 (after the reentry of the SMM missions with ACRIM I) to 1991 (before the launch of ACRIM II on UARS) only one radiometer,

²⁶ACRIM I on SMM, ERB on Nimbus 7, ACRIM II on UARS, VIRGO on SOHO, ACRIM III on ACRIMSAT, and TIM on SORCE.

-0.003±0.003

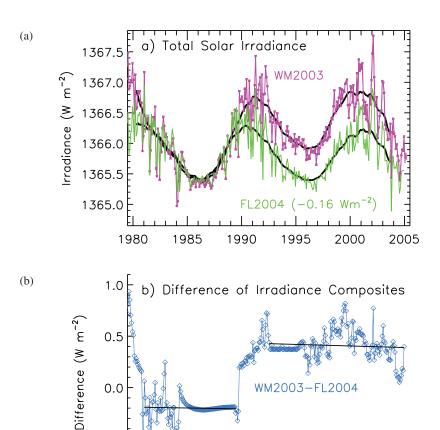


FIGURE 3.8 Compared in the panel labeled (a) are the irradiance composites of Willson and Mordvinov (2003) (WM2003, red symbols) and Fröhlich and Lean (2004) (FL2004, green solid line). Their differences, shown in panel (b), have no significant trend between January 1981 and June 1989, nor after July 1992. The approximate 3-year jump from mid-1989 to mid-1992 produces higher irradiance levels in 1996 relative to 1986, which Scafetta and West (2005) assume to be an upward "trend between minima during solar cycles 21-23" associated with a 22-year solar cycle. SOURCE: J.L. Lean, Comment on "Estimated solar contribution to the global surface warming using the ACRIM TSI satellite composite" by N. Scafetta and B.J. West. *Geophys. Res. Lett.* 33:L15701, doi:10.1029/2005GL025342, Copyright 2006 American Geophysical Union.

-0.002±0.004

-0.5

slope =

on the Nimbus 7 spacecraft, sustained the total irradiance record. Unfortunately, that radiometer lacked in-flight sensitivity tracking and was further found to be susceptible to the platform environment (e.g., movement, thermal, power) in ways that were not adequately quantified. A composite record that assumes no instrumental drifts in the Nimbus 7 radiometer shows a shift between successive solar minima (in 1986 and 1996), which has been misinterpreted as an upward irradiance trend, even though, in reality, it is a jump (Figure 3.8), and thus more likely of instrumental rather than solar origin. The possibility of such an upward tend in recent decades has spawned studies attributing as much as 30 percent of recent global warming to solar irradiance. The issue remains under debate and the elimination of TSIS from NPOESS severely reduces the imminent resolution of this issue. As Earth's only true external forcing, and with known variations arising from the Sun's activity, inadequate knowledge of future solar forcing guarantees ambiguity in climate change attribution.

The value of a reliable, uninterrupted record of solar irradiance extends well beyond the most visible and obvious applications of climate change simulations and policy making regarding global warming. The external climate forcing quantified by a precise, continuous, long-term record of solar irradiance provides a unique opportunity to

understand and characterize poorly known climate processes and sensitivity. Even after a decade of research and four IPCC assessments, uncertainties of climate sensitivity from all forcing mechanisms remain largely unchanged. From a climate modeling perspective, short-term climate sensitivities, such as to decadal forcing by the solar irradiance cycle, are calculated to be so small in amplitude (and lagged by many years) as to be undetectable in the temperature record as a result of the long thermal time scales of the ocean response. However, an accumulating body of empirical evidence questions the legitimacy of this response scenario and suggests particularly that climate responses to solar radiative forcings are not yet fully understood. Continued measurements of the Sun's 11-year cyclic behavior can improve modeled climate responses and reduce the uncertainties in forcing assessments.

Global surface temperature changes that are in phase with the solar cycle are evident in both instrumental and space-based temperature records (e.g., Figure 3.9). They suggest that climate response to solar irradiance forcing involves dynamical motions within the atmosphere in addition to thermal processes. Both recent and paleoclimate data suggest that the hydrological cycle is especially sensitive and may involve ENSO- and NAO-like interactions (e.g., Shindell et al., 2006; Ammann et al., 2007; van Loon et al., 2004). The results are motivating improvements

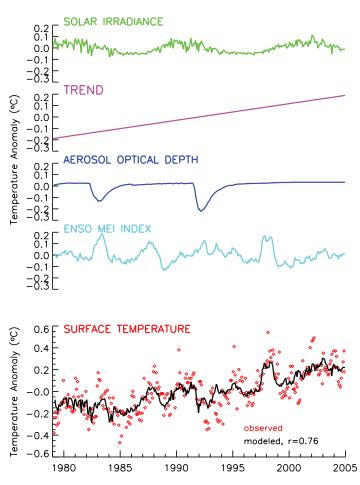


FIGURE 3.9 Four primary sources of global, monthly mean, surface temperature variations are shown in the top two panels, determined from multiple regression of the observed record. In the top panel, changes attributed to solar variability are compared with an upward trend, which tracks increasing concentrations of anthropogenic gases (the net forcing of greenhouse gas warming and tropospheric aerosol cooling). ENSO (light blue) and volcanic influences (dark blue) are compared in the middle panel. In the bottom panel, an empirical model that combines all four influences (solid dark line) is shown superimposed on the measured temperature anomalies (symbols). See also Lean (2005). SOURCE: Judith L. Lean, Naval Research Laboratory.

and expansions of the GCMs, which are typically not able to reproduce the empirical Sun-climate associations. Since the solar-induced surface temperature changes may be driven by a combination of direct visible-near IR solar forcing of the surface and troposphere, as well as solar UV-induced changes in stratospheric ozone, solar radiative forcing is a unique tool for deciphering the processes by which the surface and atmosphere interact in response to radiative forcing.

A record of the *spectral* irradiance that composes the Sun's total radiative output commenced in 2002 with SIM observations on SORCE. Although of much shorter duration, covering thus far only the descending phase of solar cycle 23, an uninterrupted time series of solar spectral irradiance is important to climate change research because solar radiative forcing and atmospheric and climate responses are all strongly wavelength dependent. In particular, variations in solar UV irradiance, which are an order of magnitude larger than the visible and near-IR changes, alter the ozone layer and stratosphere, forcing indirect climate change from stratospheric-tropospheric couplings.

In pursuit of improved understanding and advanced capability, a new generation of general circulation climate models is being developed in which state-of-the-art representations of the stratosphere (for example, with upper height "lids" near 80 km and interactive ozone chemistry) replace the few "buffer" (inactive) atmospheric layers that represent stratospheric processes in most current GCMs (Rind et al., 2007). Time-dependent simulations with the new models require as input the actual solar spectral irradiance variations, taking into account the strong wavelength dependence of the variations rather than assuming that spectral irradiance variations are wavelength-independent, and simply mimic the total. In future IPCC and other assessments, spectral irradiance will likely be requisite inputs for GCM simulations since models that input simply total irradiance and lack proper stratospheres are clearly inadequate. A continued, uninterrupted record of solar spectral irradiance observations simultaneously with the longer, more precise total irradiance record is necessary to ensure that these inputs are reliable.

Ironically, demanifesting TSIS from NPOESS terminates the solar irradiance record even as recognition of the potentially pervasive and subtle nature of climate responses to solar forcing is growing. Without TSIS on NPOESS, the total solar irradiance record will terminate after the flight of the total irradiance monitor (TIM) on Glory, which, based on its nominal 3-year mission duration, could occur as early as 2011.²⁷ The spectral solar irradiance record, which is provided via the spectral irradiance monitor (SIM), will also terminate at the end of the SORCE mission, which, as noted earlier, could occur after less than one solar cycle of observations. Lacking an ongoing, uninterrupted observational record, knowledge of solar forcing for climate simulations and attribution and assessment studies will need to be estimated from models of irradiance variations. These models are based on analysis of the current record, which is too short to quantify possible long-term trends.

TSIS (Figure 3.10) is a fully mature, state-of-the-art solar irradiance sensor that measures both total and spectral (200 nm to 0.2 micron) irradiance. Both of its instruments—TIM and SIM—have benefited significantly from the injection of cutting-edge technological advances; both have also been operating essentially flawlessly on SORCE since 2002. TSIS is relatively small and entirely self-contained; the bolometric devices used by both TIM and SIM are by design self-calibrating. Both TIM and SIM have multiply redundant components to account for in-fight sensitivity drifts. Extensive preflight calibration and characterizations are conducted, and neither ancillary data, nor formation flying is needed.

Finding: An uninterrupted record of measurement of solar irradiance is of unique value for both climate change science and for policy making. Solar irradiance was highly ranked in terms of providing a historical record of global climate, requirements for data continuity, and consequences of a data gap (question 1), measurement maturity (question 5), uniqueness (question 6), and use in development of synthesis products (question 7); however, it

²⁷Glory's hydrazine propulsion module will contain enough fuel for at least 36 months of service. Note that the French PICARD mission carries a total irradiance sensor that will fly from 2009-2011 and should overlap the operation of Glory.

²⁸Advances include phase-sensitive signal detection, NiP black cavity surfaces, and NIST-measured apertures. See G. Kopp, G. Lawrence, and G. Rottman, The Total Irradiance Monitor design and on-orbit functionality, in *Telescopes and Instrumentation for Solar Astrophysics* (S. Fineschi and M.A. Gummin, eds.), Proceedings of SPIE Volume 5171, SPIE, Bellingham, Wash., 2004, doi: 10.1117/12.505235, available at http://glory.gsfc.nasa.gov/publications/TIM_Paper.pdf.

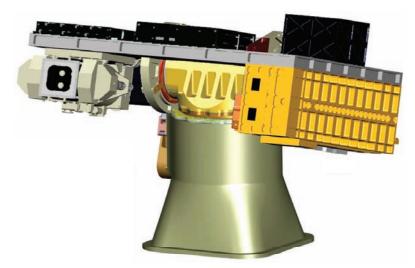


FIGURE 3.10 The NPOESS/TSIS sensor comprising the Total Irradiance Monitor (TIM) and the Spectral Irradiance Monitor (SIM) mounted on solar tracking platform (TPS). SOURCE: Courtesy of the TSIS team at the Laboratory for Atmospheric and Space Physics.

received somewhat lower rankings on other factors, including its role in climate prediction (question 3),²⁹ reanalysis (question 4), and usage in other disciplines (question 9). **Overall, solar irradiance was prioritized in the second tier of climate science capabilities.**

Preferred Recovery Strategy and Other Mitigation Options

The maturity, demonstrated longevity, and relatively minor payload accommodation requirements would appear to make TSIS ideally suited for integration with operational platforms such as NPOESS. However, if remanifesting on NPOESS is not practicable, the committee prefers the strategy of flying TSIS on a series of small, independent, free-flying, solar-pointing spacecraft. This approach provides the flexibility to achieve the overlap necessary to secure a highly precise continuous solar irradiance record, while a dedicated Sun-pointing spacecraft offers several advantages over non-solar-pointing platforms.³⁰

Flights of opportunity could also provide an effective mitigation strategy. With a solar pointing gimbal (required to allow TSIS to point continuously towards the Sun), the small TSIS sensor is readily accommodated in a range of orbits. There are no external auxiliary requirements and rapid procurement is possible due to a fully mature design and active instrument team. However, relative to a dedicated free flyer, flights of opportunity have additional risk for a data gap from launch delays that may arise independently of TSIS (for example, by other instruments or the spacecraft).

Finding: While both total and spectral solar irradiance are important to climate science, the committee noted a higher relative priority for restoration of *total* solar irradiance compared to spectral solar irradiance. Of the two, total solar irradiance is a more mature, less complex, and less costly measurement. Further, it has a longer current climate data record at risk than spectral irradiance. Therefore, should funding constraints preclude development of both TIM and SIM components of the original TSIS suite, the committee recommends that measurement continuity of TIM be given the higher priority.

²⁹This reflects committee member judgments regarding the range of variability in TSI and the sensitivity of predictions to such variability. ³⁰For example, it removes the need for the platform to carry a solar-pointing gimbal, which is approximately equal in mass and cost to the TSIS sensor itself.

Recommendation: The agencies should consider use of an appropriate combination of small, low-cost satellites and flights of opportunity to fly TSIS (or at least TIM) as needed to ensure overlap and continuity of measurements of total solar irradiance.

Aerosol Properties

Related NPOESS Sensor

APS

Post-Nunn-McCurdy Status

"A demanifested sensor"

Climate Applications

Aerosol properties

Mitigation Priority

Tier 3

Highlights of Analysis

Quantifying the effects of aerosols on the climate system remains a significant challenge. Among the most important aspects of this challenge is the need to globally monitor aerosol properties sufficiently well to determine aerosol climate forcing, which in turn requires knowledge of aerosol composition and size, and optical properties such as optical depth and particle absorption over a sufficiently broad spectral range. Satellite techniques for monitoring these aerosol properties have slowly advanced, but significant challenges remain in converting the available information to accurate measures of aerosol radiative forcing.

The physical basis for existing satellite aerosol remote sensing retrievals requires an unambiguous separation of the scattering by the atmosphere from the reflection of sunlight from the surface. Thus, most aerosol retrieval methods are applied over ocean surfaces away from sun glint, where uncertainties associated with the effects of surface reflection are generally small. While long-term records of some aerosol properties exist based on the POES Advanced Very High Resolution Radiometer (AVHRR) observations (e.g., Mishchenko and Geogdzhayev, 2007), the information available from these satellite observations is usually restricted to information only over oceans, and is limited to aerosol optical depth at a few selected spectral bands from which coarse information about particle size can also be inferred (Nakajima et al., 2001). Multichannel measurements from instruments like Terra and Aqua MODIS provide some improvement over the AVHRR observations. The multi-angle measurements of Terra's Multi-angle Imaging SpectroRadiometer (MISR) (Diner et al., 1998), though limited in spectral coverage, offer yet additional capability over land that is not available from AVHRR, MODIS, and similar single-angle imagers.

Measurement of the polarization of reflected sunlight provides the most powerful way of separating atmosphere and surface scattering effects. The Polarization and Directionality of the Earth's Reflectances (POLDER) I, II, and III instruments (Deschamps et al., 1994) have illustrated the value of spectral polarimetery (Deuzé et al., 2001). The addition of polarization information to multi-angular radiance measurements has been shown to further constrain aerosol chemical composition by providing the real part of the refractive index (Mishchenko and Travis, 1997) and provides increased sensitivity to scattering by small aerosols (Chowdhary et al., 2005). A combination of multi-angle, multispectral, and polarization capabilities thus provides the greatest potential to monitor aerosols from space with sufficient capability to determine aerosol climate forcings. This potential, however, is yet to be realized.

Polarimetry data are unique in their ability to accurately monitor aerosol abundance and size over land due to the segregation of land and atmosphere polarization effects by comparing visible (0.4-0.7 μm) and near-infrared (NIR: 0.7-1 µm) polarization, which are sensitive to atmospheric aerosols, to shortwave infrared (SWIR: 1-2.5 µm) polarization, which is relatively insensitive to atmospheric aerosols. The planned NASA Glory mission will carry the Aerosol Polarimetry Sensor (APS) to improve on current aerosol sensing platforms, by combining POLDERlike spectral multi-angular measurements with an order-of-magnitude improvement in polarization accuracy and precision, allowing substantial improvement in aerosol properties assessment.³¹

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³¹The relatively large footprint of the instrument (approximately 5 km at nadir compared to 1 km or less for MODIS and VIIRS), however, raises concerns about cloud contamination that can affect the interpretation of data in the vicinity of clouds. Cloud clearing for Glory will use

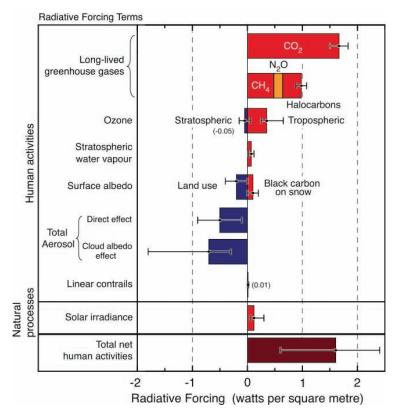


FIGURE 3.11 Summary of the principal components of the radiative forcing of climate change. All these radiative forcings result from one or more factors that affect climate and are associated with human activities or natural processes as discussed in the text. The values represent the forcings in 2005 relative to the start of the industrial era (about 1750). Human activities cause significant changes in long-lived gases, ozone, water vapor, surface albedo, aerosols, and contrails. The only increase in natural forcing of any significance between 1750 and 2005 occurred in solar irradiance. Positive forcings lead to warming of climate and negative forcings lead to a cooling. The thin black line attached to each colored bar represents the range of uncertainty for the respective value. SOURCE: P. Forster, V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, Changes in Atmospheric Constituents and in Radiative Forcing, FAQ 2.1, Figure 2, p. 136 in *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (S. Solomon, D. Qin, M. Manning, M. Marquis, K. Averyt, M.M.B. Tignor, H. LeRoy Miller, Jr., and Z. Chen, eds.), Cambridge University Press, Cambridge, U.K. and New York, N.Y., available at http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf.

Aerosol direct forcings and aerosol indirect forcings via their effects on clouds have the largest uncertainty of all the principal components of the radiative forcing of climate change (Figure 3.11) and past uncertainties attached to aerosol forcings have allowed the fitting of models to historical temperature records using climate sensitivities from 2 to 5 K (or even larger) for a doubling of CO₂ (Knutti et al., 2002). The APS instrument (together with model estimates of the anthropogenic fraction of aerosol optical depth) should considerably reduce the uncertainty associated with aerosol direct forcing. This should improve climate models because both the climate sensitivity

high-spatial-resolution nadir-viewing cloud cameras carried on board the same satellite. The expected performance of APS was discussed at "Glory Science Advisory Team Meeting," January 17-18, 2006, Boulder, Colorado (see http://lasp.colorado.edu/glory/meetings/2006/). Regarding retrieval of aerosol characteristics in the presence of clouds, see, for example, the following presentations: Michael Mishchenko, "Glory APS Science Overview," Brian Cairns, "APS Instrument," and Yoram Kaufman, "Separating Clouds from Aerosols."

and the aerosol forcing have been uncertain, allowing models with high (low) climate sensitivity to be combined with large (small) negative aerosol direct forcing to fit the past temperature record.

Finding: The originally planned APS aerosol property measurements ranked in the third tier of climate priorities. This judgment is based on recognition of the high importance of aerosol property measurement in climate science, tempered by the belief that the measurement remains a fertile area of active research with evolving measurement requirements. While aerosol properties ranked highest amongst the climate capabilities in terms of its role in climate prediction (question 3), its overall lower prioritization is largely due to lack of an existing data record or role in reanalysis, low measurement maturity, and need for ancillary data (questions 1, 4, 5, and 6).

Preferred Recovery Strategy and Other Mitigation Options

The committee strongly supports flight of APS on the NASA Glory mission. The experience gained with Glory APS should allow the capabilities of this instrument, especially with respect to its ability to monitor cloud properties, to be better defined.

Recommendations:

- NASA should continue its current plan to fly the APS on Glory.
- NASA and NOAA should continue to mature aerosol remote sensing technology and plan for the development of operational instruments for accommodation on future platforms and/or flights of opportunity.

Ocean Color

Related NPOESS Sensor

Post-Nunn-McCurdy Status

"A reduced coverage sensor"
Performance degradation is also expected

Climate Applications
Aerosols, ocean color

Tier 3

Highlights of Analysis

Monitoring of variability and change in the ocean ecosystems is a key part of a comprehensive climate observing system—understanding the spatial and temporal changes in ocean biology is a critical component of the Earth system and is fundamental to diagnosing the interaction between the physical climate system and biogeochemical cycles. Moreover, the ocean's biological processes are expected to change dramatically in response to ocean acidification, declining sea ice, inputs of meltwater, and changes in upwelling regimes, blooms of harmful algae, and even responses to proposed bioengineered approaches for carbon sequestration involving ocean biology (e.g., iron fertilization).

Imagery of water-leaving radiances in the visible and near-infrared wavelengths provides information about the space-time scale variability of the ocean, while derived products provide information about phytoplankton chlorophyll variability, and thus about ocean ecosystems.

MODIS Aqua³² and SeaWiFS data have been fundamental to the development of the ocean color climate data record over the past decade, as both instruments offer the best ocean color and aerosol information from orbit

³²In contrast to the experience of the Science Team for MODIS on the afternoon EOS Aqua platform, the MODIS Science Team for Terra has yet to provide stable ocean color data products, despite many person years of effort, due to a variety of issues including failure of the pre-launch sensor characterization, substantial radiometric signal degradation on orbit (up to 40 percent), and limitations with the on-orbit calibration

available since the demise of the Coastal Zone Color Scanner (CZCS) sensor 10 years earlier. VIIRS specifications promise similar spectral coverage (no chlorophyll fluorescence band), spectral bandwidths, radiometric dynamic range, accuracy, sensitivity, and spatial resolution to MODIS and SeaWiFS.

A VIIRS instrument was planned for each of the three orbits in the pre-Nunn-McCurdy NPOESS program: one on the early morning (5:30 AM local), mid-morning (9:30 AM local), and early afternoon (1:30 PM local) missions. However, the VIIRS measurements of particular interest to the ocean color community (Vis/NIR bands especially) will likely suffer from both reduced coverage due the loss of the NPOESS mid-morning orbit and the degraded accuracy from cross-talk among the Vis/NIR bands caused by an optical filter assembly which lowers the effective signal-to-noise ratio (SNR). Recent interactions between the ocean color scientific community and NASA (Siegel and Yoder, 2007, and response by S. Alan Stern—see Appendix C) demonstrate community concern about these issues and government limitations to address them without additional funding and prioritization.

The loss of the NPOESS 09:30 mid-morning orbit leaves only 05:30 terminator and 13:30 afternoon orbits. The terminator orbit offers little sun reflectance even over the "day side" of the terminator for aerosol and ocean color measurements, and is not suitable for ocean color, terrestrial, and many atmospheric applications. It is important to recognize that the remaining 13:30 orbit, while well suited for these measurements, was not intended to provide the sole measurement vantage point for ocean color because of the deleterious effects of sun glint over portions of the oceans caused by near-specular bright sun reflections masking ocean color signals as shown in Figure 3.12.³³

Unfortunately, in addition to the reduced coverage caused by the elimination of the 09:30 NPOESS orbit, the NPP VIIRS sensor has developmental manufacturing anomalies associated with spectral bands particularly critical to both aerosol and ocean color measurements (Box 3.2). These are the visible and near-infrared (Vis/NIR) bands between 0.4 and 1 µm within which optical cross-talk due to spectral filter manufacturing anomalies have compromised both their precision and accuracy for certain products. The 13:30 orbit NPP VIIRS sensor anomalies are not likely to be corrected,³⁴ and the next opportunity for launch of an ocean color-compliant VIIRS sensor in a 13:30 orbit will be on NPOESS C1, which will launch no earlier than 2013.

The current U.S. and international ocean color sensor capabilities are summarized in Table 3.1. The SeaWiFS instrument design life was reached in 2000, and the system was almost shut down years later. MODIS Terra reached its design life in 2004, and MODIS Aqua has also recently exceeded its design life. The earliest MODIS replacement will be VIIRS NPP, which is now scheduled for June 2010. Together, the loss of the 09:30 NPOESS orbit and the reduced VIIRS Vis/NIR spectral performance for NPP combine to severely degrade the quality of future VIIRS aerosol and ocean color data upon which the climate and science communities have come to depend from MODIS and SeaWiFS. With no action, it is very likely that MODIS and SeaWiFS will terminate operations years ahead of the first launch of a satisfactorily operating VIIRS sensor for ocean color, and even then the missing 09:30 orbit will create a roughly 50 percent reduction in temporal and spatial coverage (unless a suitable international ocean color capability complementary to VIIRS becomes available).

Some current and future international sensors have similar specifications to the current NASA sensors, however stronger partnerships must be made to ensure that detailed instrumental characterization, including post-launch

system. Past experiences with ocean color sensors have produced a set of requirements for achieving accurate ocean color imagery (McClain et al., 2006). As demonstrated with MODIS Terra, errors in the prelaunch quantification of these sensor attributes are almost impossible to resolve on orbit because their effects are convolved and can vary with solar and sensor viewing geometries. Difficulties with Terra's ocean color measurements are also briefly summarized in Bryan Franz, NASA Ocean Biology Processing Group, "MODIS Terra Ocean Processing Status," January 16, 2007, available at http://oceancolor.gsfc.nasa.gov/DOCS/modist_processing/.

³³Well before either SeaWiFS or MODIS was launched, orbit simulations showed that two orbits were required to meet the ocean color threshold globally as a function of time. Simulations demonstrated, as MODIS later proved, that observations from a single orbit (either 09:30 or 13:30) would suffer from large "outage" areas over the ocean surface. The simulations also demonstrated that obtaining data daily from both the 09:30 and 13:30 orbits would allow the vast majority of those areas masked by sun glint in one orbit to be viewable from the other so that the ocean color EDR could be met. The combination of both the 09:30 and 13:30 orbits was demonstrated to be essential to practical global ocean color observations.

³⁴S. Alan Stern, associate administrator of the Science Mission Directorate, NASA Headquarters, letter to Drs. Siegel and Yoder, University of California, Santa Barbara, dated November 20, 2007, reprinted in Appendix C of this report.

³⁵The delay in NPP launch until June 2010 was announced by NOAA while this report was in preparation. This latest delay is to accommodate a slip in the schedule for delivery of the VIIRS instrument.





FIGURE 3.12 Moderate Resolution Imaging Spectroradiometer (MODIS) image of the Canary Islands. Sun glint is a significant impediment to ocean color retrieval coverage, "washing out" significant sectors of the orbital swath—unless mitigated through a tilting mechanism (as with SeaWiFS) or through multiple orbit planes. SOURCE: Courtesy of Courtesy of Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC.

calibration/validation processing, are made available with the imagery. Obtaining consistent, climate-quality data from multiple ocean color satellite sensors requires a diverse suite of focused and closely coordinated activities including design and characterization of the sensor, collection of field data, and continued broad participation of the science community (McClain et al., 2006).

Finding: Overall, restoring VIIRS degraded ocean color capabilities ranked in the third tier of climate priorities. The ocean color science community has concluded that even if VIIRS meets its sensor specification, the data are not ideal to meet existing and future ocean biogeochemistry science requirements, and additional capability beyond VIIRS is desired to adequately address ocean biology science requirements (NASA OBBWG, 2006, p. 34). However, as indicated by the discussion above, the committee recognizes the importance of ocean color observations in a climate observing system. Research points to the need to resolve diurnal time scales in ocean temperature and air-sea heat exchanges because nonlinearities in the atmosphere, in the ocean, and in the coupled system lead to rectification of the fast time scales and because daily coupling of the ocean and atmosphere in coupled models is one source of the errors found in results from these models. Clearly, the threat to ocean ecosystems is significant, and establishing a climate record of the ecosystem via ocean color has merit. Ocean

BOX 3.2 VIIRS Performance and Measurement of Ocean Color

The baseline uncorrected integrated filter assembly (IFA) currently tested on the NPP VIIRS instrument fails to meet basic Vis/NIR band sensitivity and accuracy requirements, thus causing the instrument to fail to support threshold ocean color EDR performance. Figure 3.2.1 shows the estimated accuracy, precision, and uncertainty (APU) metrics for the 551 nm water leaving radiance (nLw) for the uncorrected NPP VIIRS, simulated based on the measured laboratory performance of the sensor in the specified band (because of the nature of the assumptions that were made, the actual performance could be worse than predicted). As water leaving radiance is very low over most of the globe illustrated by the large percentage of pixels with truth radiance below 10 watts per square meter per micron per steradian (W m⁻² μ m⁻¹ sr⁻¹), it is important that the sensor be able to meet accuracy and precision requirements below 10 W m⁻² μ m⁻¹ sr⁻¹. It is clear, however, in Figure 3.2.1, that both accuracy and precision exceed the 10 percent accuracy and 5 percent precision requirements. As both accuracy and precision, then the uncertainty requirement is also not met.

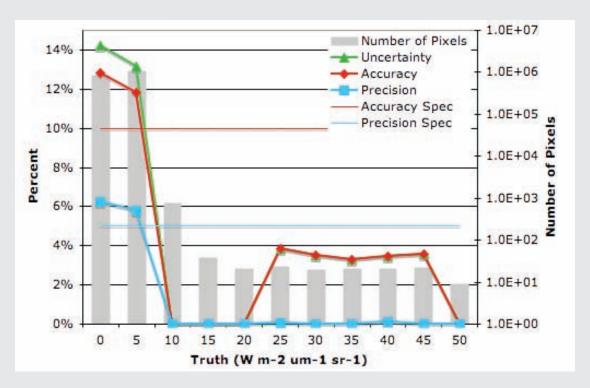


FIGURE 3.2.1 Accuracy, precision, and uncertainty (APU) metrics for the 551 nm water leaving radiance (nLw) for the uncorrected NPP VIIRS. SOURCE: K. Turpie, NASA GSFC, "Cherry-Picked (CP) IFA or Baseline (BL) Integrated Filter Assembly (IFA)? Impact of optical crosstalk to Ocean Color EDRs by two problematic filter arrays," Fourth Visible/Infrared Imager/Radiometer Suite (VIIRS) Crosstalk Technical Interchange Meeting, August 1, 2007, NPOESS Integrated Program Office, Silver Spring, Md.

TABLE 3.1 Current Ocean Color Sensors and Capabilities

Sensor	Agency	Satellite	Launch Date	Swath (km)	Resolution (m)	Bands	Spectral Coverage (nm)	Orbit
COCTS	CNSA (China)	HY-1B (China)	04/11/2007	1400	1100	10	402-12,500	Polar
CZI	CNSA (China)	HY-1B (China)	04/11/2007	500	250	4	433-695	Polar
MERIS	ESA (Europe)	ENVISAT (Europe)	03/01/2002	1150	300/1200	15	412-1050	Polar
MMRS	CONAE (Argentina)	SAC-C (Argentina)	11/21/2000	360	175	5	480-1,700	Polar
MODIS-Aqua	NASA (USA)	Aqua (EOS-PM1)	05/04/2002	2330	1000	36	405-14,385	Polar
MODIS-Terra	NASA (USA)	Terra (EOS-AM1)	12/18/1999	2330	1000	36	405-14,385	Polar
OCM	ISRO (India)	IRS-P4 (India)	05/26/1999	1420	350	8	402-885	Polar
POLDER-3	CNES (France)	Parasol	12/18/2004	2100	6000	9	443-1,020	Polar
SeaWiFS	NASA (USA)	OrbView-2 (USA)	08/01/1997	2806	1100	8	402-885	Polar

NOTE: COCTS, Chinese Ocean Color and Temperature Scanner; CZI, Coastal Zone Imager; MERIS, Medium Resolution Imaging Spectrometer; MMRS, Multispectral Medium Resolution Scanner; MODIS, Moderate Resolution Imaging Spectroradiometer; OCM, Ocean Colour Monitor; POLDER-3, Polarization and Directionality of the Earth's Reflectances; SeaWiFS, Sea-viewing Wide Field-of-view Sensor. SOURCE: Courtesy of the International Ocean Colour Coordinating Group, available at http://www.ioccg.org/sensors/current.html.

color observations are strongly recommended to extend the measurement record, but in terms of the committee's climate ranking factors, restoration of VIIRS degraded capabilities was not scored among the highest priorities. Ocean color did not rate highly with respect to use in reanalysis (question 4), uniqueness (question 6), and use by IPCC and CCSP (question 7).³⁶

Preferred Recovery Strategy and Other Mitigation Options

The IPO and VIIRS team should continue to make all practical efforts to improve VIIRS performance to meet specifications and avoid the anticipated degradation in accuracy. To address reduced sensor coverage, the agencies should work with their international partners toward flying a more capable imager, of the class expected from a fully functional VIIRS, in the mid-morning orbit. This might include consideration of a VIIRS flight of opportunity aboard an international mission and/or cooperation on MERIS-2 or OCM-2 efforts.³⁷ A free flyer tailored to the needs of the ocean color community is another possibility; the benefits of this approach have been noted in several recent publications.³⁸

³⁶With the maturation of coupled biophysical ocean models, we may look toward assimilation of ocean color, but it is not yet a routine process. In contrast, physical variables are assimilated and essential to climate modeling.

³⁷The need for a dedicated ocean color mission to accommodate instrument calibration and other needs was expressed at the June 2007 workshop and a community letter to NASA (Siegel and Yoder, 2007). Note that the present committee's analysis is based only on the relevance of the measurement/sensor to the needs of the climate science and applications communities.

³⁸ Ibid. Also see NASA OBBWG (2006).

Recommendations:

- The NPOESS Integrated Program Office should consider any practical mechanisms to improve VIIRS performance for NPP and ensure that all specifications are met or exceeded by the launch of NPOESS C1.
- The agencies should ensure that adequate post-launch calibration/validation infrastructure is in place, including oversight by the scientific community (see Chapter 4), to ensure the production of viable ocean color imagery.
- To address reduced sensor coverage, the agencies should work with their international partners toward flying a fully functioning VIIRS or a dedicated sensor on a mission of opportunity in Sunsynchronous orbit. The agencies should also work with international partners to ensure community access to ocean color and ancillary calibration/validation data from international platforms during the gap likely to be experienced prior to launch of C1.

Ozone Profiles

Related NPOESS Sensor

OMPS-Limb

Post-Nunn-McCurdy Status

"A demanifested sensor" Now restored to NPP

Climate Applications

Ozone profiles

Mitigation Priority

Tier 3

Ozone profile measurements are needed to both monitor the ozone recovery process and understand the impacts of climate change on ozone layer recovery. The trend of increasing depletion of global stratospheric ozone observed during the 1980s and 1990s is no longer occurring; however, it is not yet clear whether these recent changes are indicative of ozone recovery due to the decrease in ozone-depleting gases associated with the implementation of the Montreal Protocol (Forster et al., 2007). Adequate vertical resolution is needed to resolve ozone structure in the lower stratosphere, where most halogen-related ozone depletion occurs. Several studies have shown that ozone changes in the tropical lower stratosphere are very important for both the magnitude and sign of ozone radiative forcing (Ramaswamy et al., 2001). Continued limb monitoring of ozone concentrations is required to estimate the vertical profile of ozone changes, which is needed to estimate climate forcing.

Ozone limb measurements contribute to an understanding of ozone changes in the lower stratosphere and hence the adequacy of the Brewer-Dobson circulation in climate models.³⁹ These models are not yet sufficiently robust to understand changes in water vapor and ozone in the lower stratosphere (so forcing beyond that associated with ozone could be improved if measurements of the ozone profile continue).

OMPS-Nadir and OMPS-Limb were designed as an integrated instrument suite to meet both monitoring and climate science goals. The nadir viewing portion of OMPS provides total column and profile ozone measurements comparable to the TOMS instrument. However, nadir-viewing instruments lack sufficient vertical resolution and sensitivity to depict altitude-dependent processes associated with ozone recovery. OMPS-Limb was intended to complement the OMPS-Nadir measurements, providing higher fidelity vertical profile ozone data to continue and improve upon the daily global data produced by the current ozone monitoring limb-viewing systems, the Solar Backscatter Ultraviolet radiometer (SBUV)/2. The limb profile measurement together with total ozone was to provide strong constraints on the magnitude of the forcing. Post-Nunn-McCurdy, only the OMPS-Nadir portion of the originally planned OMPS suite is retained. While retention of OMPS-Nadir satisfies obligations under

³⁹The Brewer-Dobson circulation pattern sets up between equator and pole in the winter hemisphere and results in column ozone distributions that are low in the tropics and high in the polar regions. Many models predict an increased circulation associated with an increase in greenhouse gases; see H.K. Roscoe, The Brewer-Dobson circulation in the stratosphere and mesosphere—Is there a trend? *Advances in Space Research* 38(11):2446-2451, 2006.

the Montreal Protocol to monitor total ozone, climate science needs for continued and improved vertical profile measurements remain unmet.

Although the continuity and overlap of ozone profile measurements have provided intercomparison opportunities for calibration in the past, such overlap may not be critical if flights of a freshly calibrated instrument are planned for the future (NRC, 2000).

Finding: Overall, ozone profiles ranked in the third tier of climate priorities. Ozone profiles ranked highly in measurement maturity (question 5), but low in terms of need for continuity, uniqueness, contribution to understanding of the climate system, and contribution to other disciplines (questions 1, 6, 8, and 9).

Preferred Recovery Strategy and Other Mitigation Options

With the deletion of the OMPS-Limb sounder, no monitoring of ozone profile below the ozone peak (where most ozone depletion occurs) would be possible during the period when NPOESS and MetOp would operate. The committee supports the recommendation made by the NRC decadal survey to restore OMPS-Limb to NPP, and strongly endorses the agencies' commitment to finish integration and testing of the already-built NPP OMPS-Limb instrument. The committee further notes that OMPS was designed as an integrated instrument suite with common electronics; therefore, a cost-benefit analysis is warranted to determine whether the suite should be restored to additional NPOESS platforms based on the level of integration in the original instrument design.⁴⁰

Recommendation: The committee supports current agency plans to reintegrate OMPS-Limb on NPP. The agencies should consider the relative cost/benefit of reintegration of OMPS-Limb capabilities for NPOESS platforms carrying OMPS-Nadir based on the degree of integration inherent in the instrument's original design.

RATIONALE FOR PRIORITIZATION: GOES-R LOST CAPABILITIES

Geostationary Advanced Hyperspectral Sounding

Related GOES-R Sensor HES

Current Status

OLD R School

"A demanifested sensor"

Climate Applications

High temporal resolution temperature and moisture profiles for process studies

stud

Tier 2

Mitigation Priority

Geostationary sounders provide the capability of observing diurnal variation of climate variables including cloudiness, surface (sea and land) temperature, and atmospheric temperature and humidity. Although limited to regional (rather than global) coverage, the environmental space-time scales sampled by geostationary sounders strongly relate to climate change, including the frequency and intensity of severe weather (e.g., severe thunderstorms, flash flooding, hurricanes, winter storms). Spatial scales of 25 km or less and temporal scales of minutes to hours, best achieved from geostationary orbit, are needed to, for example, capture the evolution of the pre-convective environment as circulations develop and as low-level moisture is advected into a region. Further, by monitoring spectrally resolved radiances for the same location, local zenith angle, and local time every day, regional water vapor budgets in the western hemisphere can be determined. This, in turn, could lead to an improved analysis of

⁴⁰The NASA-NOAA report indicates that restoring OMPS-Limb capability to the OMPS is "cost-effective compared to alternative approaches." As the committee was not provided any specific information on costs, and in any event is not using cost as a factor in its prioritization, a relative value assessment is considered beyond the scope of this report.

local climates, and better projections. Winds derived from the current GOES system are an important contributor to contemporary reanalysis efforts. An advanced GEO sounder would provide better winds (and moisture) at more vertical levels, with improved height assignments, in future reanalysis projects.

The fast processes of the climate system, such as the development of storms as part of Earth's weather systems, integrate their effects to alter climate through a number of important mechanisms that are thought to be changing in time. The moistening of the upper troposphere associated with deep convection, for example, is believed to be changing over time in such a way as to accelerate the water vapor feedback (Soden et al., 2005). The utility of advanced IR sounders has been demonstrated for monitoring climatic changes in upper tropospheric moisture (Lerner et al., 2002). Pre-convective environment observing capabilities provided by a hyperspectral GEO sounder also directly support the forecasting of storms and the prediction of the character of storms (such as potential convective intensity and moisture availability, among other characteristics that are of substantial importance to these aspects of climate change.

Operational soundings from GOES began with the GOES-I series of satellites—initiated with the VAS demonstration mission through the Operational Satellite Improvement Program (OSIP).⁴³ An advanced sounding capability has been advocated for many years to meet emerging needs in both climate and weather communities.⁴⁴ GOES-R was to carry an advanced sounder, HES, with hyperspectral capability to greatly improve upon previous GOES sounders. The hyperspectral capability of an advanced GEO sounder would enable observation of the sources and sinks and the transport of pollutant and greenhouse gases, including CO₂, CO, O₃, N₂O, CH₄, and H₂O, and improve understanding of climate variability and change, while simultaneously providing benefits to society through superior weather analysis and forecasts. The termination of the sounder on GOES-R will instead end this long-term record after GOES-P.

A geostationary hyperspectral sounder builds upon polar orbiting hyperspectral sounding experience gained from the currently operating AIRS and IASI instruments and planned NPOESS-era CrIS. Mesoscale models and assimilation systems have continued to advance to the point where the spatial and temporal resolution provided by hyperspectral sounding from GEO can be readily exploited. Capitalizing on geostationary orbit's unique vantage point, a hyperspectral geostationary sounder would also provide an important data set for the intercalibration of

⁴¹The source and sinks of anthropogenic radiatively active gases remain a primary concern in determining the extent of the effect of greenhouse gases on global climate. However, an equally important (yet poorly understood) influence on climate is the distribution of increased atmospheric water vapor associated with a speeding up of the hydrologic cycle. The atmospheric portion of the hydrologic cycle is complex, and operates on both short and long time scales. The fast processes associated with this mechanism, such as cloud formation and the related intra- and inter-cloud radiative impacts, influence cloud nucleation, longwave radiation, albedo feedbacks, and ultimately the surface energy balance. On decade to century time scales, the impact of increased water vapor is realized through alterations in large-scale cloud distribution, which reflect both the water-vapor distribution and the hydrologic cycle's response. Also, the latent heating of clouds and its radiative effects influence the large-scale atmospheric circulation and hydrologic cycle—additional complexities that need to be better understood. Excerpt from NRC, *Decade-to-Century-Scale Climate Variability and Change: A Science Strategy*, National Academy Press, Washington, D.C., 1998, p. 57.

⁴²The steering of tropical storms is generally governed by the adjacent environmental wind flow, which can often be cloudless, and defined by observations of the altitude-resolved motions of water vapor molecules. A geostationary hyperspectral sounder can help in the prediction of the initiation, or lack thereof, of tropical storm development in an otherwise relatively cloudless (or broken cloud) environment from its observations of sea-surface temperature, moisture, vertical shear of the horizontal wind, and often inhibiting Saharan Air Layer (Atlantic storms). It has been shown through adaptive observation modeling, that uncertainties and biases in hurricane landfall predictions (e.g., in the Gulf of Mexico) can be reduced through increased observations that are geographically remote (e.g., over Colorado or Greenland) 24-36 hours in advance. Through the use of many orthogonal vertical wind fields, retrieved through feature-tracking across many gridded water vapor profiles, significantly improved environmental wind fields can be assimilated into NWP models, resulting in improved predictability and forecast quality.

⁴³Prior to 1981, NASA and NOAA cooperated effectively in developing new operational satellite systems. At that time, NASA typically funded "first unit" builds of weather satellites and their instruments and then transitioned proven capabilities to NOAA (and its predecessor, the Environmental Science Services Administration) for operational use. This cooperation was guided by a formal agreement established in 1973, the Operational Satellite Improvement Program (OSIP), which was funded at about \$15 million per year. The budgets for NASA and NOAA reflected this agreement. NASA used its funding to develop prototype sensors, fly them on high-altitude aircraft, and transition them to research spacecraft for evaluation. Successful instruments were then provided to NOAA for transition to operational status. The program fell victim to NASA budget pressures and an Office of Management and Budget (OMB) desire to offload "routine" functions from NASA, and was canceled in 1982. See p. 51 of NRC (2003).

⁴⁴See, for example, Science Benefits of Advanced Geosynchronous Observations: (The Scientific Basis for the Advanced Geosynchronous Studies Program), Draft Report, March 1998. Available at http://goes.gsfc.nasa.gov/text/ags_science.html.

BOX 3.3 Geostationary Hyperspectral Sounding Benefits for Weather Applications

In addition to nowcasting and short-term forecasting, our society increasingly relies on NWS 1- to 7-day forecasts for all aspects of public health and safety, transportation, agriculture policies, etc. The GEO advanced sounder will contribute to improving the consistency and accuracy of the 1- to 7-day forecasts, giving decision makers additional confidence with longer lead times. Specifically, an advanced GEO sounder would provide:

- Real-time continual pollution monitoring, severe storm warnings (e.g., tropical and convective), and aviation weather (e.g., visibility, icing, turbulence, volcanic ash, FAA NextGen 4D Weather Cube).
- · Input to mesoscale NWP.
- Pre-convective conditions for heavy rainfall potential.¹
- Surface observations—with an increased probability of clear viewing of the sea (temperature, sea state) and land (temperature, vegetation index) and detection of diurnal signals.
- Atmospheric soundings with rapid refresh, providing improved atmospheric stability trends (pre-convective storm outlooks).

¹Clouds are generally not a significant inhibitor for detecting the conditions antecedent to severe thunderstorm development, as advanced geostationary IR sounding instruments would observe the thermodynamic changes (moisture flux, temperature lapse rate changes, and associated capping inversion erosion) which occur before the deep convection and opaque cloudiness takes place. Hyperspectral resolution can also allow observation of the thermodynamic structure below semi-transparent cirrus anvils, which often cover the sky after the convection is initiated, thereby making it possible to observe where subsequent convection will take place. Finally, the higher spatial resolution of an advanced GEO sounder makes it possible to more frequently retrieve profiles between clouds and adjacent to fronts. While traditional IR-based sounders are inherently limited in their sounding abilities in cloudy regimes, the high spectral, spatial, and temporal capabilities of a hyperspectral sounder on a GEO platform would allow profiles above the cloud tops, and the potential for full profiles in broken cloud regimes.

radiometers in low Earth orbit, as all polar satellites will under-fly it to provide the potential for 4-5 intercomparisons per day.

In addition to its role in observing the diurnal variation of climate variables, the incorporation of geostationary hyperspectral sounding capabilities on future GOES spacecraft would allow significant advances in weather analysis and forecasting (see Box 3.3). Noting the significant advances promised by the GEO hyperspectral sounder, members of the operational and research segments of the weather, water, climate, and environmental communities issued letters of support for an early flight for a GEO advanced sounder, and closure of the imminent GEO sounding gap. The National Weather Association (NWA) issued a Letter of Support for the GOES-R series high spectral resolution sounder, and the American Meteorological Society's Committee on Satellite Meteorology and Oceanography⁴⁵ issued a consensus statement "On the Importance of Deploying a GEO Advanced Sounder without Delay."

⁴⁵The AMS committee membership is found at http://www.ametsoc.org/stacpges/CommitteeDisplay/CommitteeDisplay.aspx?CC=SATMET. Chris Velden and Philip Ardanuy, members of the NRC committee authoring this report, also sit on the AMS committee.

^{46&}quot;Geostationary sounders provide unique, rapidly updated temperature and moisture profile measurements. The ability to vertically resolve water vapor in the atmosphere—the "basic fuel" for severe thunderstorms—is crucial for monitoring and predicting hazardous weather conditions. Large variations in atmospheric water vapor occur over fine scales of ten kilometers in the horizontal, one kilometer in the vertical, and over tens of minutes. Continuous monitoring is essential. Hyperspectral infrared measurements from GEO would continuously describe the clear-sky vertical moisture structure, more than double the temperature profile information content from today's sounders, and permit new wind profiling capabilities by constantly tracking retrieved water vapor profile features at many discrete levels. Assimilated into the next generation of numerical weather prediction models and used for "nowcasts," observations from the GEO advanced sounder could enable improved analyses of severe weather and hurricanes, with the potential to save lives while also providing important

Some of the recent difficulty in developing the Hyperspectral Environmental Sounder (HES) intended for GOES-R may be ascribed to the complexity of including coastal waters imagery requirements on top of those for hyperspectral infrared sounding. NOAA's Analysis of Alternatives⁴⁷ included the possibility of flying just the advanced sounder portion of the HES suite. The analysis found that low-risk conceptual designs for an operational sounder exist and recommended a flight of a demonstration sounder as early as possible—conceivably as early as 2012.

The committee noted that while plans for international geostationary imaging missions were on a solid foundation, such was not the case for geostationary hyperspectral infrared sounding. The U.S. loss of initiative for providing geostationary hyperspectral soundings, even with the strong recommendations from the decadal survey, is disturbing; this loss of leadership⁴⁸ is particular vexing as Europe, Japan, and China proceed with firm plans for geostationary hyperspectral sounding.

Finding: Provision of hyperspectral infrared sounding in GEO orbit ranked within the second highest tier of prioritized climate capabilities. The advanced sounder capability scored particularly high in terms of contributing to improved understanding in related disciplines (question 9) and measurement uniqueness (question 6).

Preferred Recovery Strategy and Other Mitigation Options

The preferred strategy for the recovery of advanced geostationary hyperspectral sounding is consistent with the decadal survey, NOAA's Analysis of Alternatives, and community letters: an earliest possible flight of a demonstration mission in GEO orbit, followed by the earliest possible provision of sustained and robust operational GEO hyperspectral sounder series—beginning no later than GOES-T.

An early flight demonstration would serve to both realize the anticipated societal benefits in a timely and cost-effective fashion, and to prepare for the measurement's operational transition. A proactive and cooperative effort between NASA and NOAA to develop a realistic demonstration plan is needed in order to prepare for the proposed operational GOES-T flight. The committee strongly encourages NOAA and NASA to partner together to demonstrate and complete development of this important observing capability. For example, a renewed NASA-NOAA partnership, perhaps through a mechanism similar to the Operational Satellite Improvement Program, could deliver an early hyperspectral demonstration sounder that could either be manifested on GOES-S or fly "in formation" on a separate spacecraft, as EUMETSAT is considering for the hyperspectral sounder on the Meteosat Third Generation (MTG). An early flight of a sounder prototype for the GOES-R series would demonstrate both the technology and the measurement benefits, which could then be followed by an operational sensor on (or in formation with) GOES-T.

Recommendation: NASA and NOAA should plan an earliest-possible demonstration flight of a geostationary hyperspectral sounder, supporting *operational* flight in the GOES-T time frame.

new climate observations. Other applications include the areas of aviation and air quality." From, Satellite Meteorology and Oceanography Committee, AMS Scientific Activities and Activities Commission Consensus Statement, October 3, 2007. Available at http://www.eumetsat.int/idcplg?IdcService=GET_FILE&dDocName=PDF_MTG_MMT5.

⁴⁷See John J. Pereira, NOAA, *Analysis of Alternatives for Advanced Sounding and Coastal Waters Imaging*, presentation to committee on April 23, 2007, available at http://www7.nationalacademies.org/ssb/SSB_NPOESS2007_Presentations.html.

⁴⁸A primary recommendation of the decadal survey is that "the U.S. Government . . . renew its investment in Earth observing systems and restore its leadership in Earth science and applications" (NRC, 2007, p. 12).

Geostationary Coastal Waters Imagery

Related GOES-R Sensor HES-CWI

Current Status "A demanifested sensor"

Climate Applications Ocean primary productivity and the carbon cycle

Mitigation Priority Tier 4

The coastal ecosystem, at the boundary between land and ocean, is driven by climate-scale dynamics that affect both ocean and watershed processes. The coastal region is forced by diverse processes at multiple time scales, including tides (12- and 24-hour), diurnal heating (24-hour), and storm and other synoptic weather events, as well as long-term (climate trend) time scales. Deconvolving this superposition of the short and long time scales in coastal waters requires geostationary sampling. The Coastal Waters Imager (CWI) component of HES was to provide high temporal and spatial resolution observations, enabling improved water quality monitoring, coastal hazard assessment, navigation safety, ecosystem health awareness, ⁴⁹ natural resource management in coastal and estuarine areas, coral reef health monitoring, and development of nowcast and forecast models of the coastal ocean. With the cancellation of HES, coastal waters imagery capabilities in the GOES-R time frame were essentially lost.

While the primary benefit of geostationary coastal waters imagery is to coastal monitoring, management, and remediation,⁵⁰ there are important secondary benefits related to regional climate response that would be difficult to assess by any other means.⁵¹ These benefits are primarily associated with the higher temporal resolution afforded by use of a geostationary orbit, and higher spatial resolution intended for the CWI. Higher temporal resolution would serve to resolve rapid changes associated with climate-relevant processes (e.g., due to tides, coastal currents, and severe storms) and allow for more opportunities for cloud-free coastal waters viewing. CWI's 300 m spatial resolution was intended to augment the existing long-term ocean color measurement record, extending it from open oceans and large basins into littoral regions, estuaries, and rivers to provide valuable measurements of coastal and shelf waters properties. These regions are currently undersampled due to the inability of current ocean color sensors, such as SeaWiFS, MODIS, and soon VIIRS, to resolve ocean color measurements on scales of 1 km or less, as well as their spectral inability to perform atmospheric corrections in these turbid regions.⁵² CWI's ability to dwell for long durations on areas of interest would allow for higher-quality images through improved signal-to-noise associated with longer integration times; higher quality images combined with higher spatial resolution would greatly enhance the ability to image and monitor complex areas like Chesapeake Bay, Puget Sound, San Francisco Bay, and the Great Lakes (see Figure 3.13).

There is currently no capability, beyond limited point in situ data, for determining the sensitivity of the coastal regions to climate change. In its report to Congress, the U.S. Commission on Ocean Policy expressed growing concern about the health and future of coastal waters and noted the importance of spaceborne sensors to the Integrated Ocean Observing System (IOOS) (U.S. Commission on Ocean Policy, 2004). Geostationary coastal waters imagery would provide needed coastal monitoring and decision support capability, while also monitoring the effects of climate change in coastal regions. CWI was to provide a resource for monitoring these climate-sensitive regions, including key indicators such as chlorophyll and related pigments, frequency and extent of harmful algal

⁴⁹For example, CWI would provide critical observations on phytoplankton abundance and community structure in the coastal zone.

⁵⁰Storm events such as hurricanes can rapidly affect coastal water quality by suspending sediments and flooding rivers and estuaries with nutrients and land-based pollution. Tides, winds (such as the land/sea breeze), river runoff, and upwelling can rapidly affect coastal regions through transportation of harmful algal blooms, pollution, and oil spills. Identifying and closely tracking these types of features as they approach the shore would greatly improve the ability to manage coastal resources.

⁵¹Climate change in coastal waters may result in part from a greater frequency of storms and consequent runoff events, increasing the likelihood of event-type responses, such as harmful algal blooms, which are best observed from a geostationary vantage point.

⁵²Current sensors acquire one image per day and clouds and sun glint can obscure the view of an area. By sampling every three hours, coastal waters imaging would provide coastal managers and scientists with access to coastal ocean imagery throughout the day, and the capability to choose or combine images to provide a view that is free of clouds. The Advanced Baseline Imager (ABI) on GOES-R could be used to select cloud free areas for imaging.

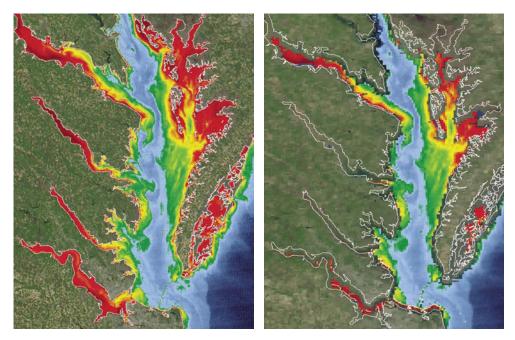


FIGURE 3.13 Water clarity is a performance indicator for restoration efforts in the Chesapeake Bay. These images of the lower Chesapeake Bay illustrate the improvement in spatial resolution needed for coastal waters. The higher spatial resolution of the 250-meter Moderate resolution Imaging Spectroradiometer (MODIS) image (left) provides unmatched detail (turbid waters are shown in red; clear waters in blue) in the rivers and from the same sensor (right). SOURCE: Courtesy of Naval Research Laboratory; from "Coastal Waters Imaging on GOES-R: A Key Component of the Integrated Ocean Observing System," available at http://cioss.coas.oregonstate.edu/CIOSS/Documents/GOESbrochure.pdf.

blooms (HABs), and turbidity from changes in rainfall patterns and river flows. The GEO-CAPE mission, recommended for launch in the 2013-2016 time frame by the *Earth Science and Applications from Space* decadal survey (NRC, 2007), is intended to address many of these important coastal ecosystem observation needs, although it is fundamentally a research-driven mission rather than an operational capability.

Finding: In terms of climate prioritization, coastal waters imagery ranked in the lowest (fourth) prioritization tier. As a fundamentally new measurement, coastal waters imagery ranked highly for measurement uniqueness (question 6); however, it was ranked near the bottom of most other prioritization questions. This is perhaps unsurprising, as coastal waters imagery is primarily intended to serve other, non-climate applications and research needs.

Preferred Recovery Strategy and Other Mitigation Options

Provision for coastal waters imaging should be considered by the agencies based on non-climate applications.

SUMMARY OF COMMITTEE RECOMMENDATIONS FOR NEAR-TERM RECOVERY

The sections above summarize the impacts on the climate-related measurement capabilities of NPOESS and GOES-R that resulted from the June 2006 Nunn-McCurdy certification of NPOESS and the decision in September 2006 to eliminate HES on GOES-R. In Chapter 2 the committee details its prioritization process, which resulted in an ordered list of the importance of these changes. In Table 3.2, the committee summarizes its recommendations for a *near-term* strategy to restore the climate capabilities that were endangered by the program restructurings.

TABLE 3.2 Summary Recommendations for Mitigation of Lost or Degraded Climate Capabilities

Lost or Degraded Climate Capability			
in NPOESS Low Earth Orbit	Recommendation		
Tier 1 Microwave Radiometry	 NASA and NOAA should initiate a study as soon as practicable to address continuity of microwave radiometry and to determine a cost-effective approach to supplement the AMSR-2, carried on the Japanese spacecraft GCOM-W, with another microwave radiometer of similar design. The agencies should also consider the feasibility of manifesting a microwave radiometer on a flight of opportunity or free flyer to cover the microwave radiometry gap anticipated with a delay in accommodation of MIS until NPOESS C2. The agencies should provide funding for U.S. participation in an AMSR-2 science team to take full advantage of this upcoming microwave radiometer mission. The NPOESS Integrated Program Office should continue with its plans to restore a microwave sounder to NPOESS C2 and subsequent platforms, with an emphasis on SUAG priorities 1 through 3 (core radiometry, sounding channels, and soil moisture/sea surface temperature). NASA and NOAA should devise and implement a long-term strategy to provide sea-surface wind vector measurements. The committee finds important limitations in the planned reliance on a polarimetric radiometer for this measurement; instead, the preferred strategy is timely development and launch of the next-generation advanced scatterometer mission, that is, the Extended Ocean Vector Winds Mission (XOVWM) recommended in the 2007 NRC decadal survey Earth Science and Applications from Space. 		
Radar Altimetry	A precision altimetry follow-on mission to OSTM/Jason-2 (i.e., Jason-3) should be developed and launched in a time frame to ensure the necessary mission overlap. The agencies' long-term plan should include a series of precision altimetry free flyers in non-Sun-synchronous orbit designed to provide for climate-quality measurements of sea level.		
Earth Radiation Budget	To minimize the risk of a potential data gap, the committee reiterates the recommendation of the 2007 <i>Earth Science and Applications from Space</i> decadal survey to manifest the CERES FM-5 on NPP. The agencies should further develop an ERB instrument series and provide for subsequent flights on Sun-synchronous platforms to continue the Earth radiation budget long-term record.		
Tier 2 Hyperspectral Diurnal Coverage	The CrIS/ATMS instrument suite should be restored to the 05:30 NPOESS orbit to provide improved hyperspectral diurnal coverage and support atmospheric moisture and temperature vertical profile key performance parameters.		
Total Solar Irradiance	The agencies should consider use of an appropriate combination of small, low-cost satellites and flights of opportunity to fly TSIS (or at least TIM) as needed to ensure overlap and continuity of measurements of total solar irradiance.		
Tier 3	,,		
Aerosol Properties Ocean Color	 NASA should continue its current plan to fly the APS on Glory. NASA and NOAA should continue to mature aerosol remote sensing technology and plan for the development of operational instruments for accommodation on future platforms and/or flights of opportunity. The NPOESS Integrated Program Office should consider any practical mechanisms to improve VIIRS performance for NPP and ensure that all specifications are met or exceeded by the launch of NPOESS C1. The agencies should ensure that adequate post-launch calibration/validation infrastructure is in place, including oversight by the scientific community, to ensure the production of viable ocean color imagery. To address reduced sensor coverage, the agencies should work with their international 		
	partners toward flying a fully functioning VIIRS or a dedicated sensor on a mission of opportunity in Sun-synchronous orbit. The agencies should also work with international partners to ensure community access to ocean color and ancillary calibration/validation data from international platforms during the gap likely to be experienced prior to launch of NPOESS C1.		
Ozone Profiles	The committee supports current agency plans to reintegrate OMPS-Limb on NPP. The agencies should consider the relative cost/benefit of reintegration of OMPS-Limb capabilities for NPOESS platforms carrying OMPS-Nadir based on the degree of integration inherent in the instrument's original design.		
Lost or Degraded Climate Capability in GOES-R Geostationary Earth Orbit	Recommendation		
Tier 2 Geostationary Hyperspectral Sounding	NASA and NOAA should plan an earliest-possible demonstration flight of a geostationary hyperspectral sounder, supporting <i>operational</i> flight in the GOES-T time frame.		
Tier 4 Geostationary Coastal Waters Imagery	Provision for coastal waters imaging should be considered by the agencies based on non-climate applications.		

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4

Elements of a Long-Term Climate Strategy

The dramatic reduction in NPOESS and GOES-R contributions to climate measurement following Nunn-McCurdy certification and program cost-reduction efforts necessitates a near-term strategy of the kind outlined in Chapter 3 for recovery of crucial climate capabilities. Yet without proactive consideration of the elements of a viable long-term climate observational measurement strategy, important lessons from the well-intentioned but poorly executed merger of the nation's weather and climate observation systems (Box 4.1) will be of little benefit. This chapter outlines the key elements of a long-term climate strategy.

OPERATIONAL VERSUS SUSTAINED CLIMATE OBSERVATIONS

The NRC decadal survey *Earth Science and Applications from Space* describes the overlapping nature, similarities in, and differences between exploratory, operational, and sustained observations. Briefly, exploratory measurements are new observations designed to shed light on poorly understood processes and so advance scientific understanding; operational measurements serve day-to-day critical activities such as weather forecasting that require high reliability and near-real-time data availability; and sustained measurements support the development of long-term records of key variables that are required to uncover slowly evolving dynamics or long-term climate changes. The inclusion of sensors that make climate-relevant measurements in an operational observing system muddles the distinction to some extent.

Whereas a sensor's inclusion on an operational system in theory provides long-term access to space and clearly identified launch opportunities, it also implies significant overhead associated with requirements for high reliability and near-real-time data availability. For the climate sensors originally to be flown on NPOESS, being part of an operational system meant sharing both a satellite platform and a ground data system tailored to meet operational objectives rather than climate science needs. From a climate science perspective, this resulted in sub-optimal spacecraft capabilities (e.g., the absence of a lunar calibration) and ground system design (e.g., the inability to archive or provide data for reanalysis) at increased cost compared to traditional narrowly focused research missions. Clearly, the desirability of conducting sustained climate observations as part of an operational program should be balanced with consideration of the pragmatics of combining the two and the overall cost-effectiveness of such an approach.

See Chapter 3 of Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (NRC, 2007).

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BOX 4.1 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 the Polar-orbiting Operational Environmental Satellites and the Defense Meteorological Satellite Program. 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 observation and information-processing program (like the Earth Observation System); therefore, the community developed a new strategy for obtaining climate measurements from NPOESS. That led 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, that 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 the 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, whereas climate studies 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. That 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 (the Department of Commerce's NOAA) included climate and other broad environmental issues, the mission of the other (the Department of Defense's Air Force) did not. That led to conflicting priorities between the two agencies, which by law were required to share program costs on a 50-50 basis.

SOURCE: Reprinted from Box 3.1 in Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (NRC, 2007), p. 63.

The situation from the perspective of both research and operational agencies was characterized in a previous NRC report (NRC, 2000c, p. 8):

Although the operational and the research approaches can appear to conflict, there are features of both that are essential for climate research and monitoring. However, the operational agencies are necessarily wary of assuming responsibility for new requirements that may be open ended in an environment that is cost constrained. The research agencies are similarly concerned about requirements for long-term, operational-style measuring systems that might inhibit their ability to pursue new technologies and new scientific directions. Despite their need for long-term commitments to measure many critical variables, they wonder about relying on operational programs that might decrease the level of scientific oversight as well as opportunities for innovation.

In some cases there is clear overlap between sustained and operational measurement objectives, and a single measurement can provide for both needs. However, the specific measurement requirements for each application can vary, leading to less synergism than was initially intended. The ALT instrument on NPOESS, for example, is a well-designed and very capable instrument; however, climate science clearly requires an orbit different from

what can be accommodated by the NPOESS architecture, rendering the hoped-for dual-purpose measurement useful only for operational applications. A long-term climate strategy should explicitly take into consideration both the similarities in and the differences between the sustained measurements required for climate research and the exploratory and/or operational measurement objectives of other agency programs so as to maximize synergies while avoiding incompatible implementations arising from inadequate understanding of each application's specific measurement requirements.

Calibration, Characterization, Stability, and Continuity

Data used for characterizing climate trends must meet tighter requirements for calibration, characterization, and stability than are needed for non-climate trend-environmental data because the variations in signals of interest for climate studies tend to be small compared with the variations among sequential environmental measurements made during a single orbit (Box 4.2). Yet without exception, the space-based measurements of the climate system—including climate forcings, feedbacks, and responses—are made with instruments for which the degree of uncertainty in their absolute calibration exceeds the magnitude of the changes that they seek to measure, and whose stability is limited by drifts in optical, electrical, thermal, geometrical, orbital, and other in-flight parameters. The acquisition of reliable climate records therefore relies (until the measurements are adequately benchmarked against absolute standards) on the measurements having high repeatability (precision) over the years to decadeslong time scales of climate change.

Sensor calibrations can change between the ground and space, and they tend to change more rapidly during the beginning of a mission. Individual instruments are calibrated in-flight by using on-board sources or repeated reference observations of the Sun, stars, the Moon, or stable terrestrial features (e.g., deserts). However, since the design lifetimes of individual instruments and space missions are generally of insufficient duration for continuous observation on the longer time scales associated with climate change, most climate records are compiled from data gathered in overlapping missions with cross-calibrated instruments.

A strategy for maintaining the long-term precision of successive measurements of climate parameters is to build in sufficient overlap of successive missions to enable reliable cross-calibration between instruments, in principle compensating for uncertainties in absolute calibration. In contrast, a gap between the measurements made by successive climate-monitoring instruments (even by instruments that are nominally "identical") increases uncertainty in the time series of the derived climate parameter because two non-overlapping time series can be connected only via knowledge of their absolute uncertainties. An added degree of uncertainty that exceeds the magnitude of the geophysical change being measured effectively terminates the usefulness of that climate time series for trend analysis. An adequate period of overlap is therefore essential both to remove calibration biases among independent measurements and to achieve in-flight calibration of the new sensors by in-flight comparison with the more stable, in-flight-characterized existing sensor. The actual period of overlap for achieving continuity of climate time series such that the long-term repeatability is higher than the geophysical variations may depend on a number of factors, including the amplitude and time scales of variability inherent in the quantity being measured and the rate and nature of the sensors' sensitivity to changes. The required overlap period has been evaluated in a number of ways and is typically reported to be about 1 year.

The passive microwave record of sea ice (Figure 4.1), for example, is one of the longest consistent climate records obtained from satellite observations and has become a key indicator of climate change, signaling unexpectedly large and accelerating decreases in sea ice extent, especially in the recent past. Maintaining the consistency of this 30-year record, as well as ensuring that the recorded trends signify real climate change rather than instrument artifacts, requires sustained climate-quality observations. Overlapping coverage and inter-sensor calibration between successive instruments over at least one annual cycle are essential to maintaining the integrity of the time series for analysis of climate change. A gap in a critical time series for a variable such as sea ice would not simply represent a temporal lapse—it would in fact end a long-term record of climate impacts at a time when researchers have witnessed record-low sea ice extent for multiple years. Prior NRC reports have identified and discussed a variety of other climate records for which continuity of observations is essential, including solar irradiance (measured by TSIS), energy balance quantities (measured by CERES), ozone (measured by OMPS), and surface and atmospheric temperatures.

BOX 4.2 Measurement Requirements to Detect Climate Trends

Calibration refers to the process of comparing the output of a sensor to "truth" radiance to provide conversion factors (calibration coefficients) that allow in-flight sensor digital numbers to be converted to radiances. Generally limited to radiometry, calibration is an example of characterization, which has a broader meaning.

Characterization is the assessment of the radiometric performance of a sensor not only in terms of "accuracy" but also in terms of other parameters, including, for example, sensitivity (signal-to-noise ratio), dynamic range, spatial resolution (e.g., modulation transfer function), spectral bandpass, and other parameters that must be known, but do not require calibration coefficients to convert sensor output to a geophysical parameter. Both calibration and characterization are essential to knowing how well a sensor measures the spectral radiance and/or spatial character of the scene within its field of view.

Stability refers to how well a sensor maintains constancy in response over time to a constant input. Instruments are seldom inherently stable enough to guarantee accuracy over time using the initial calibration coefficients. For this reason, sensors such as MODIS have been developed with built-in calibration reference capability so that the radiometric calibration coefficients can be updated frequently enough to guarantee that the corrected data are accurate over time. Moreover, other characterization parameters can also be updated in orbit, including spectral bandpass, spectral response, and spectral band registration.

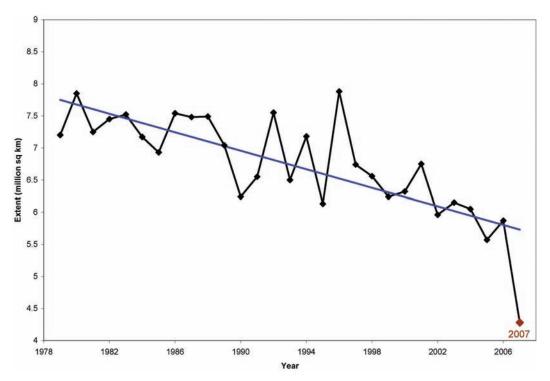


FIGURE 4.1 Arctic sea ice extent from passive microwave sensors 1979-2007. SOURCE: Courtesy of the National Snow and Ice Data Center.

TABLE 4.1 Data Requirements for Operational and Climate Applications

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Data System Attribute	Operational Applications	Climate Applications
Archiving	Focus is on rapid assimilation into Numerical Weather Prediction models; "old" data have limited operational utility	Archiving is critical, enabling both multiple reprocessing cycles and library-like access by the climate community to climate data records
Reprocessing	Typically out of scope; no resources allocated	Mandatory, with the throughput capacity requirements growing at approximately "1X" (1X permits the processing of 24 hours worth of data in 1 day) per year—for every year of measurements
Latency	The ideal latency is "zero" (real time); new innovations such as SafetyNet for NPOESS support <30-minute data collection	Latency is much less important than data completeness, calibration continuity and stability, robust on-orbit instrument characterization, and rigorously validated and improved algorithms (both code and theoretical basis)
Reliability	Assured "up times" >99% are mandatory, as the production supports mission critical (e.g., life-saving) applications	Determined through best-value model that balances the total life-cycle cost of the system against throughput efficiency
Configuration management	Must facilitate frequent and immediate "reactive" (event-driven) and "science- based" upgrades	Scope includes algorithms, primary and ancillary input data, output products and metadata, and calibration coefficients; usually frozen for an entire reprocessing cycle

Appropriate Data System Design

Considerable attention should be paid to the development of data system architecture that best serves the multitude of stakeholders needing access to climate-relevant data. Data systems used for exploratory research (e.g., NASA DAACs) provide demonstrated long-term archival capabilities and reprocessing capacity but lack intuitive interfaces for applications end users. Operational data systems, such as the NPOESS data system, are designed for low data latency and high reliability rather than the active archival and evolutionary reprocessing required for establishment and maintenance of climate data records. An appropriate and cost-effective data system for climate measurements should seek to leverage the best attributes of both systems, while avoiding cost-driving capabilities that are not associated with climate needs.

While the need for sustained climate measurements is clear, the need for "operational" climate data streams in near-real time is less obvious. The requirements for climate versus other operational systems typically differ in several significant dimensions, specifically including divergent needs for archiving, reprocessing, latency, reliability, and configuration management (Table 4.1). Given the extent of these disparities, the agencies should consider the level of ground system integration that is both desirable and cost-effective in future observation systems.

A flexible data system architecture is required to accommodate the multitude of climate data sources (e.g., interagency, international, space-based, ground-based) while allowing for upgradability as technology improves. Clear standards and well-defined interfaces are needed to enable more streamlined user access to existing and planned climate-relevant data sets, without having to negotiate the myriad specialized and uncoordinated systems currently in use. Numerous NRC reports provide guidance on the attributes of an effective climate data system (NRC, 1999a,c, 2000a,b, 2004a).

CLEAR NATIONAL POLICY FOR PROVISION OF LONG-TERM CLIMATE MEASUREMENTS

Much of climate science depends on long-term, sustained measurement records. Yet, as noted in many previous NRC and agency reports, the nation lacks a clear policy to address these known national and international needs. For example, an ad hoc NRC task group (NRC, 1999b, p. 4) stated as follows:

No federal entity is currently the "agent" for climate or longer-term observations and analyses, nor has the "virtual agency" envisioned in the [U.S. Global Change Research Program] succeeded in this function. The task group

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endorses NASA's call for a high-level process to develop a national policy to ensure that the long-term continuity and quality of key data sets required for global change research are not compromised in the process of merging research and operational data sets.²

A coherent, integrated, and viable long-term climate observation strategy should explicitly seek to balance the myriad science and applications objectives basic to serving the variety of climate data stakeholders. The program should, for example, consider the appropriate balance between (1) new sensors for technological innovation, (2) new observations for emerging science needs, (3) long-term sustainable science-grade environmental observations, and (4) measurements that improve support for decision making to enable more effective climate mitigation and adaptation regulations (NRC, 2006). The various agencies have differing levels of expertise associated with each of these programmatic elements, and a long-term strategy should seek to capitalize on inherent organizational strengths where appropriate.

Elements of this needed national policy are discussed in the following sections, which draw heavily on previous NRC reports and careful consideration of the needs of sustained versus operational observations as discussed above.

Clear Agency Roles and Responsibilities

The issues noted above were recognized explicitly in the NRC decadal survey *Earth Science and Applications from Space*, whose authors stated, "The committee is concerned that the nation's civil space institutions (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 federal government" (NRC, 2007, p. 13). In turn, this prompted one of the report's most important recommendations: "The Office of Science and Technology Policy, in collaboration with the relevant agencies and in consultation with the scientific community, should develop and implement a plan for achieving and sustaining global Earth observations. This plan should recognize the complexity of differing agency roles, responsibilities, and capabilities as well as the lessons from implementation of the Landsat, EOS, and NPOESS programs" (p. 14). *The present committee fully endorses the need for clarified agency roles and responsibilities, consistent with inherent agency strengths, and reiterates this important recommendation of the decadal survey.*

International Coordination

The committee recognizes the importance of international cooperation in obtaining climate quality measurements from space. As noted in the June 2007 workshop report (NRC, 2008, p. 38):

With limited financial and human resources, a response to GCOS [Global Climate Observing System] requirements can be achieved only through enhanced international cooperation. Such cooperation should involve global planning with international contributions, in such a way that implementation problems encountered by an individual agency do not dramatically affect the global system. It was recognized that a number of missions planned in Europe will be of great value for climate analysis and that there is an acute need for better international collaboration and awareness spanning the full spectrum of activities from high-level data access agreements to pragmatic documentation exchange.

The committee agrees with a workshop participant's assessment that "there has not been a concerted strategy for sustained climate observations from space [and that] . . . the climate community has relied on suboptimal sen-

²A similar view was expressed in *Adequacy of Climate Observing Systems*, which stated, "There has been a lack of progress by the federal agencies responsible for climate observing systems, individually and collectively, toward developing and maintaining a credible integrated climate observing system" (NRC, 1999a, p. 5).

sors to create a climate record, resulting in significant challenges in terms of handling bias differences, orbit drift, data gaps, and spectral differences between follow-on instruments when reprocessing multi-satellite data—often at considerable cost" (NRC, 2008, p. 37). That there remains no internationally agreed upon and ratified strategy

While the committee has no doubt that organizations such as CEOS, CGMS, WMO, and the evolving GEO will provide important insight and support for developing such a strategy, it believes the issue is of such paramount importance that it must be addressed, and eventually implemented on an intergovernmental level where binding agreements can be reached. The committee also finds merit in recent international plans to establish so-called virtual constellations consisting of a set of existing (or planned) ground or space-based assets from different partners that are mobilized in a coordinated manner for greater efficiency or improved data products. Constellations may involve formation flying or coordinated operation scheduling and data distribution, thus potentially including both real and virtual constellation elements. Virtual constellations can be designed to provide better coverage, in temporal, spatial, and/or spectral information, and improved data management and dissemination. This can both

With respect to climate missions, the creation and use of constellations provide significant benefits through:

Coordinating use of existing systems providing global data;

improve information products and reduce net costs for operating agencies.

for climate observations from space remains an area of grave concern.

- Generating the potential for advanced, integrated products;
- Coordinating the analysis of gaps in current operations and future mission deployment plans;
- · Providing standards for interoperability and facilitating data uptake into models; and
- Provision of routine global coverage for sustained observations and increased redundancy.

Recommendation: To obtain benefits of the kind that virtual constellations of assets could provide, it is strongly recommended that the research and operational agencies coordinate their development, operations, standards, and products with international partners. In addition to the obvious coordination of observations and ground systems, national agencies should incorporate standard calibration and validation processes including the use of ground-based and lunar virtual calibrations, and establish "best practices" recommendations for measurements, calibration, and use of standards.

COMMUNITY INVOLVEMENT IN THE DEVELOPMENT OF CLIMATE DATA RECORDS

The National Research Council has produced a number of reports on the subject of climate data records (CDRs), many having been motivated by concerns over the future availability of satellite-based climate-quality data records. Some of these reports offer opinions about what is needed to ensure CDRs from satellites and recommend guiding principles for their development (e.g., NRC, 1999a,c, 2000a-c, 2003, 2004a,b). The implied demise of climate-focused satellite observations from NPOESS, a consequence of the Nunn-McCurdy certification, adds to the ongoing concern about the lack of organized commitment to the development of CDRs.

It has been stressed in many NRC and other reports that CDRs are far more than time series of EDRs and that their production requires considerable scientific insight. The careful sensor calibration, sensor characterization, and algorithm refinements necessary for high-quality CDRs require access to uncalibrated measurements (see Box 4.3). CDRs require periodic reanalysis and reprocessing as data sources improve, error characteristics become clearer, and retrieval algorithms and assimilation methods advance. In addition, the requirements for generating CDRs vary greatly from one record to another. Thus development of CDRs requires a broader engagement of the community than is required for the development of EDRs, and independent teams, funded to calculate CDRs from uncalibrated satellite measurements, are essential if the requirements for quality expected of CDRs are to be met.³

³This recommendation can be found in NRC reports dating back to at least 2000. See, for example, the following: "Science teams responsible for algorithm development, data set continuity, and calibration and validation should be selected via an open, peer-reviewed process (in contrast to the approach taken with the operational integrated data processing system (IDPS) and algorithms, which are being developed by sensor contractors for NPOESS)" (NRC, 2000c, p. 4).

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The NRC report Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations identifies key state variables—temperature, precipitation, humidity, pressure, clouds, sea-ice and snow cover, SST, carbon fluxes, and soil moisture—for establishment of CDRs (NRC, 2003). To ensure that data records comprise more than a series of isolated variables, these data records must be produced in such a way as to provide a means to monitor processes of the climate system through the construction and monitoring of joint distributions of parameters.

Although the need to institutionalize the management and oversight of CDR data stewardship is obvious, the CDR implementation process and its stewardship have to be distributed across the community where relevant expertise and competencies exist, typically outside any one agency. An important lesson from the NPOESS process is that putting together an advisory council or analogous product teams does not necessarily ensure the preservation of the community's interest throughout the process. Rather, there is a need to establish "new community relationships by engaging a broader academic community, other government agencies, and the private sector in the development and continuing stewardship of satellite climate data records" (NRC, 2004a, p. 99) by integrating the external community into the CDR implementation processes, taking it well beyond using this community in a superficial advisory role.

The committee believes that the research community has to be involved at every level of CDR development, from identification of the variable to be measured over time as a CDR, to the determination of the level of maturity of products, to their maintenance and the eventual improvement via reprocessing. The way to develop this partnership is to solicit the community's involvement from the outset, giving it ownership in the process and funding its involvement. As noted in footnote 3, these issues are recognized in recommendations from a 2000 NRC report. Thus, while management of CDRs may be delegated to a single agency, their development, maintenance, and archiving do not necessarily need to remain exclusively within that agency, and in fact are more appropriately distributed to relevant communities who are already engaged in the production of CDRs.

Plans for implementing a CDR program have to explain how the necessary new community relationships are to be developed, how and when an advisory group that represents the external community might be formed to review CDR maturity, and how external CDR science teams responsible for both implementation and stewardship are to be formed, managed, and supported through a peer review process. Historically, insufficient allocation of resources to support this wider engagement has often been perceived as the principal impediment to progress. The key elements of successful CDR generation are outlined in Box 4.4.

CONCLUSION: A WAY FORWARD

In this report, the committee provides a prioritized, short-term strategy for recovery of crucial climate research capabilities lost in the NPOESS and GOES-R program descopes. However, mitigation of these recent losses is only the first step in establishing a viable long-term climate strategy that builds on the lessons learned from the well-intentioned but poorly executed merger of the nation's weather and climate observation systems. Specifically, a coherent, integrated, and viable long-term climate observation strategy is needed that explicitly seeks to balance the myriad science and applications objectives of climate data stakeholders, while properly considering both the similarities in *and* the *differences* among the exploratory, sustained, and operational measurements needed for climate science. The long-term strategy must provide for the requisite characterization, calibration, stability, and continuity of sensors and data, as well as for data systems designed to enable a range of climate applications. The development of a coherent national strategy for Earth observations (NRC, 2007) would support these efforts by establishing clear agency roles and responsibilities for the provision of climate-quality data and ensuring community involvement in the development of climate data records.

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NRC (National Research Council). 1999a. *Adequacy of Climate Observing Systems*. National Academy Press, Washington, D.C. NRC. 1999b. "Assessment of NASA's Plans for Post-2002 Earth Observing Missions," letter report. National Academy Press, Washington,

NRC. 1999b. "Assessment of NASA's Plans for Post-2002 Earth Observing Missions," letter report. National Academy Press, Washington, D.C., April 8.

NRC. 1999c. Making Climate Forecasts Matter. National Academy Press, Washington, D.C.

BOX 4.3 EDRs Versus CDRs: An Example

The Total Irradiance Monitor (TIM) on SORCE measures total solar irradiance. Fundamentally, this involves measurement of radiant power and area (Figure 4.3.1). For TIM, area is determined by a precision aperture, and radiant power is determined by the electrical heating required to maintain constant temperature of an absorptive radiometer as sunlight is modulated.

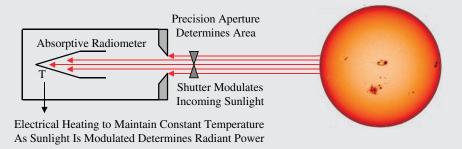


FIGURE 4.3.1 Irradiance (i.e., 1361 W/m²) requires two measurements: power and area. SOURCE: Courtesy of G. Kopp, Laboratory for Atmospheric and Space Physics, University of Colorado.

Total solar irradiance EDRs are released to the scientific community in near-real time for short-term processoriented studies. To generate the EDR, the fundamental instrument measurements are converted to TSI considering:

- 1. Aperture area [watts/m²],
- 2. Thermal background corrections (from on-orbit dark measurements),
- 3. Distance and radial velocity between the radiometer and the Sun, and
- 4. Change in cavity absorptance (from on-orbit degradation tracking).

Total solar irradiance CDRs are needed by the scientific community for studies of climate change and short- and long-term solar and climate processes. Accuracy and consistency are crucial to such studies, which generally incorporate data from multiple instrument generations. *Many more steps are involved to ensure that the best-known characterization, calibration, and stability information is fully incorporated for each instrument.* For example, they might include:

- NRC. 2000a. Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites. National Academy Press, Washington, D.C.
- NRC. 2000b. Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part I. Science and Design. National Academy Press, Washington, D.C.
- NRC. 2000c. Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part II. Implementation. National Academy Press, Washington, D.C.
- NRC. 2003. Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations. The National Academies Press. Washington, D.C.
- NRC. 2004a. Climate Data Records from Environmental Satellites: Interim Report. The National Academies Press, Washington, D.C.
- NRC. 2004b. Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond. The National Academies Press, Washington, D.C.

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- Using the most recent understanding from each instrument team of degradation, gain, and dark measurement trends, as available.
- Reprocessing entire instrument data sets throughout the mission(s) to incorporate the latest available trending data.
- Cross-calibration of current and successive TSI instruments using periods of measurement overlap to maintain continuity.
- Intercomparison of independent irradiance measurements to estimate differences in absolute accuracies and instrument stabilities with time.
- Estimation of the effects of orbit limitations on measurements used to construct daily means.
- Construction of composite TSI record by adjusting for instrument offsets and temporal drifts, using cross-comparisons from ground-based irradiance reference if available, *including time-dependent uncertainties in the composite*.
- · Seeking consistency among measurements and models to identify areas needing improved understanding.

As summarized below, the more extensive requirements for CDRs drive TIM instrument pre-flight and in-flight calibration and characterization needs:

TIM pre-flight calibrations and characterizations supporting CDR development:

- Entrance aperture geometric area and diffraction/scatter effects
- Cavity absorptance (efficiency) across solar spectral region
- · Electrical power applied to cavities from reference voltages and resistances
- · Electrical linearity calibrations across dynamic range
- Radiometer non-equivalence (mismatch between electrical and radiant heating)
- Thermistor calibrations
- Shutter response
- · Scattered light and field-of-view angular dependences
- · End-to-end comparison with ground-based irradiance reference links current and future TSI instruments

TIM on-orbit calibrations and calibration tracking supporting CDR development:

- Dark background measurements of deep space correct for instrument thermal contributions
- Degradation tracking due to solar exposure since pre-flight cavity absorptance calibration via regular infrequent simultaneous observations with lesser-used cavities
- · Servo system gain calibrations
- Pointing sensitivity

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

NRC. 2007. Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. The National Academies Press, Washington, D.C.

NRC. 2008. Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft: A Workshop Report. The National Academies Press, Washington, D.C.

¹G. Kopp and G. Lawrence, "The Total Irradiance Monitor (TIM): Instrument Design," Solar Physics 230(1):91-109, 2005.

BOX 4.4 Key Elements of Successful Climate Data Record Generation

On the basis of its review of previous NRC studies (especially NRC, 2004a and 2000c), and its members' own experience, the committee identified the following as particularly important elements of a sustained long-term program for deriving credible climate data records.

Organizational Elements

- A high-level leadership council¹—including members from different agencies, academia, and industry to
 oversee the process of defining and creating climate data records (CDRs) from satellite data. Ad hoc
 advisory committees can be established as needed.
- Science teams—formed for each CDR, consisting of a specifically appointed team of experts responsible
 for sensor calibration, algorithm design, validation, and research using the CDR. The science teams
 should have membership broadly distributed across different agencies, academia, and industry. Multiple
 subgroups within the science team should be funded to provide independent CDRs from raw (uncalibrated) satellite measurements.

CDR Generation Elements

- Sensors must be thoroughly characterized before and after launch, and their performance should be continuously monitored throughout their lifetime.
- Sensors should be thoroughly calibrated, including nominal calibration of sensors in orbit, vicarious calibration with in situ data, and satellite-to-satellite cross-calibration.
- Algorithm design must consider differences in measurements due to changes in the sensor design or satellite navigation.
- Well-defined levels of uncertainty are required. An ongoing program that includes correlative in situ measurements and model analyses is required to validate CDRs.
- Multiple teams should be funded to independently create CDRs. The multiple teams are key to providing
 the best possible end product. These teams will be responsible for calibration of satellite measurements,
 developing CDR algorithms, validation of the CDR, and refinement of CDR processing.
- Researchers must be involved who, through their research, will provide feedback on the quality of the CDRs.

Sustaining CDR Elements

- A long-term commitment of resources should be made to the generation and archiving of CDRs and associated documentation, data, and metadata.
- Access to reprocessing resources is required when better sensor calibrations and improved algorithms become available.

¹See, in NRC (2004a), pp. 3-4, especially Supporting Recommendation 1: "NOAA should utilize an organizational structure where a high-level leadership council within NOAA receives advice from an advisory council that provides input to the process on behalf of the climate research community and other stakeholders. The advisory council should be supported by instrument and science teams responsible for overseeing the generation of climate data records."

Appendixes



A

Statement of Task

An ad hoc committee will conduct an assessment and prepare a report that will:

- 1. Prioritize capabilities, especially those related to climate research, that were lost or placed at risk following recent changes to NPOESS and the GOES-R series of polar and geostationary environmental monitoring satellites. These include capabilities that were lost or degraded as a consequence of alterations in the planned constellation of spacecraft and/or the removal or reduction in scope of remaining instruments; and
 - 2. Present strategies to recover these capabilities.

In conducting its assessment, the committee will build on information from the workshop that will be conducted in June 2007 by the separately appointed NRC Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft and on the panel's report expected to be issued in August 2007.

Included in this assessment will be the committee's analysis of the capabilities and timeliness of the portfolio of missions recommended in the 2007 *Earth Science and Applications from Space* decadal survey to recover these capabilities, especially those related to research on Earth's climate, and the potential role of existing and planned spacecraft operated by international partners and the role of existing and planned civil U.S. spacecraft. The committee will also make a preliminary evaluation of the risks, benefits, and costs of placing—on NPOESS, GOES-R, or other space-based platforms—alternative sensors to those originally planned.

B

Reprinted Workshop Report

Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft: A Workshop Report (National Research Council, The National Academies Press, Washington, D.C., 2008), which summarizes the National Research Council workshop "Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft" held in June 2007 in Washington, D.C., is reprinted here in its entirety. Note that in the reprinted report's table of contents, the page numbers added in italic reflect the pagination that applies for inclusion in the current report, rather than the pages numbers of the original report. The original report is available online at http://www.nap.edu/catalog.php?record_id=12033.

Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft

A Workshop Report

Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft

Space Studies Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
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This study is based on work supported by Contract NNH06CE15B between the National Academy of Sciences and the National Aeronautics and Space Administration and Contract DG133R07SE1940 between the National Academy of Sciences and the U.S. Department of Commerce's National Oceanic and Atmospheric Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-11276-5 International Standard Book Number-10: 0-309-11276-1

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PANEL ON OPTIONS TO ENSURE THE CLIMATE RECORD FROM THE NPOESS AND GOES-R SPACECRAFT

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Preface

NPOESS, which has been driven by the imperative of reliably providing short-term weather information, is itself a union of heretofore separate civilian and military programs. . . . The same considerations of expediency and economy motivate the present attempts to add to NPOESS the goals of climate research. The technical complexities of combining seemingly disparate requirements are accompanied by the programmatic complexities of forging further connections among three different agencies, with different mandates, cultures, and congressional appropriators. Yet the stakes are very high, and each agency gains significantly by finding ways to cooperate, as do the taxpayers. Beyond cost savings, benefits include the possibility that long-term climate observations will reveal new phenomena of interest to weather forecasters, as happened with the El Niño/Southern Oscillation. Conversely, climate researchers can often make good use of operational data.¹

In January 2007, the National Research Council's (NRC's) Earth science decadal survey committee delivered to agency sponsors a prepublication version of its final report, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*.² However, prior to the delivery of that report, NASA and NOAA requested that additional items be added to the committee's statement of task. The new tasks focused on recovery of measurement capabilities, especially those related to climate research, that were lost as a result of changes in plans for the next generation of polar and geostationary environmental monitoring satellites, NPOESS and GOES-R (see Appendix A).³

By mutual agreement, the new tasks were to be addressed by a separate panel in a report that would draw on the results of a major workshop. Specifically, the new tasks were as follows:

1. Analyze the impact of the changes to the NPOESS program that were announced in June 2006 and changes to the GOES-R series as described in the NOAA testimony to Congress on September 29, 2006. These changes included reduction in the number of planned NPOESS satellites, the deletion or descoping of particular instruments, and a delay in the planned launch of the first NPOESS satellite. In addition, recent changes to the GOES-R series resulted in deletion or descoping of instrumentation and a delay in the first spacecraft launch. The committee should give

¹Excerpted from the Foreword to National Research Council (NRC), *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: II. Implementation*, National Academy Press, Washington, D.C., 2000.

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

³Note that acronyms not defined in the text, especially those denoting individual instruments and missions, are defined in Appendix D.

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particular attention to impacts in areas associated with climate research, other NOAA strategic goals, and related Global Earth Observation System of Systems/Integrated Earth Observation System (GEOSS/IEOS) societal benefit areas. 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. The committee will prioritize capabilities that were lost or placed at risk following the changes to NPOESS and the GOES-R series and present strategies to recover these capabilities. 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 changes to the NPOESS and GOES-R programs may also offer new opportunities. The committee should provide a preliminary assessment of the risks, benefits, and costs of placing—on NPOESS, GOES-R, 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.

This workshop report, prepared by the NRC's Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft, presents the initial response to this request. It summarizes the presentations and discussions at a June 19-21, 2007, workshop but does not necessarily reflect the consensus views of the panel or the NRC. A second report, which will include recommendations for a strategy to recover recently descoped observational and measurement capabilities, is scheduled for transmittal by January 31, 2008.

The workshop, titled "Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft," was held at the National Academies' Keck Center in Washington, D.C. Some 100 scientists and engineers from academia, government, and industry attended the workshop, which gave participants a chance to review and comment on the NASA-NOAA assessments of the impacts to climate observations associated with the changes made to the NPOESS program following the June 2006 Nunn-McCurdy certification, 4 as well as potential mitigation strategies. Participants also discussed the impact of the September 2006 cancellation of the HES instrument on GOES-R, which was to have contributed to NOAA strategic goals and to GEOSS/IEOS societal benefit areas. 5 The workshop was divided into morning plenary sessions and afternoon breakouts. To guide breakout discussions, participants were given templates to be filled out during discussions. The workshop agenda is shown in Appendix B.

When considering questions regarding recovery of climate observation capabilities on NPOESS, participants were asked to discuss the impacts and mitigation options associated with the June 2006 Nunn-McCurdy certification and the GOES-R descoping in terms of both the Global Climate Observing System (GCOS) essential climate variables (ECVs)⁶ and related climate data records, and in terms of the sensors themselves. Participants then reviewed the options discussed in a NOAA-NASA report to the White House Office of Science and Technology Policy (OSTP);⁷ however, participants were also asked to consider a wider universe of mitigation options, including free flyers, formation flying, and constellations; flights of opportunity; and international partner opportunities beyond the European MetOp program. At the request of OSTP, NASA and NOAA are also performing such an analysis as part of the second phase of their study, the final results of which were not available at the time of the workshop. Their preliminary assessment is summarized in Appendix C, which reproduces the text and figures of a presentation given at the workshop.

⁴See U.S. House of Representatives Committee on Science and Technology, Hearing Charter, "The Future of NPOESS: Results of the Nunn-McCurdy Review of NOAA's Weather Satellite Program," June 8, 2006, available at http://gop.science.house.gov/hearings/full06/June%208/charter.pdf.

⁵Presentations made at the April 23-24, 2007, workshop organizing meeting and presentations made at plenary sessions and notes taken on the breakout sessions at the June 19-21, 2007, workshop are available at http://www7.nationalacademies.org/ssb/SSB_NPOESS2007_Presentations.html.

⁶The GCOS was established in 1992 to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users. It is co-sponsored by the World Meteorological Organization, the Intergovernmental Oceanographic Commission of UNESCO, the United Nations Environment Programme, and the International Council for Science. For information on the GCOS ECVs, see http://www.wmo.ch/pages/prog/gcos/index.php?name=essentialvariables.

⁷NOAA-NASA, "Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals," draft white paper, January 8, 2007.

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Workshop participants were asked to consider how the following programs will or could play into a mitigation strategy in the period before and after NPOESS launches:

- 1. NPOESS Preparatory Project (NPP),⁸
- 2. Extended-phase operations of instruments on the Earth Observing System spacecraft, and
- 3. Implementation of the recommendations made in the decadal survey, *Earth Science and Applications from Space*. ¹⁰

Of the three items above, consideration of the potential impact of the decadal survey dominated participant discussions. In part, this emphasis resulted from recognition that with limited funds, recovery strategies, especially for NPOESS, would effectively compete with the new starts recommended in the decadal survey. In addition, the measurement capabilities of sensors on some of the missions recommended in the decadal survey overlap with those recently lost in the descoped NPOESS and GOES-R programs.¹¹

The organization of this report follows loosely that of the workshop agenda (Appendix B), which was designed to have participants consider the impact of changes to the NPOESS and GOES-R program according to the impact on the measurement of ECVs (breakout sessions on day 1 of the workshop) and on the specific sensors that constituted the pre-Nunn-McCurdy NPOESS and the pre-descoped GOES-R program baselines (breakout sessions on day 2 of the workshop). The panel recognized that there would be overlap in these discussions but thought it useful for participants to consider the broader issues of ECV measurement and development of climate data records apart from specific concerns about NPOESS sensors. Indeed, many workshop participants noted repeatedly that ensuring the measurement(s) of a particular climate variable(s) was only a necessary first step toward enabling the creation of time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change—that is, to generate climate data records. 12

In closing, the panel notes with deep regret the sudden death of Anthony Hollingsworth, from the European Centre for Medium-Range Weather Forecasts, on July 29, 2007. Tony was a world-class meteorologist and, as noted in the many tributes that followed his passing, a key figure in fostering international collaborations among EUMETSAT, the European Space Agency, and space agencies worldwide. At the time of his death, Tony was heading Europe's GEMS environmental monitoring project; he also was advising the panel on the international dimensions of mitigation options for NPOESS.

⁸The National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) is a joint mission involving NASA and the NPOESS Integrated Program Office. See http://jointmission.gsfc.nasa.gov/.

⁹See http://eospso.gsfc.nasa.gov/eos_homepage/description.php.

¹⁰NRC, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, The National Academies Press, Washington, D.C. 2007

¹¹For descriptions of the decadal survey missions, see Chapter 4 of NRC, *Earth Science and Applications from Space*, 2007. For discussions of decadal survey missions and NPOESS, see Chapter 2 and Tables 2.4 and 2.5 in that report.

¹²NRC, Climate Data Records from Environmental Satellites: Interim Report, The National Academies Press, Washington, D.C., 2004.

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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 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 review of this report:

Eric J. Barron, University of Texas, Craig Donlon, Hadley Centre, Met Office, United Kingdom, Dennis P. Lettenmaier, University of Washington, Ralph F. Milliff, Colorado Research Associates, and R. Keith Raney, Johns Hopkins University Applied Physics Laboratory.

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 Byron D. Tapley, University of Texas at Austin. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

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Note that in the reprinted report's table of contents, the page numbers added in italic reflect the pagination that applies for inclusion in the current report, rather than the pages numbers of the original report. The original report is available online at http://www.nap.edu/catalog.php?record_id=12033.

Summary

The nation's next-generation National Polar-orbiting Operational Environmental Satellite System (NPOESS) was created by Presidential Decision Directive/National Science and Technology Council (NSTC)-2 of May 5, 1994, whereby the military and civil meteorological programs were merged into a single program. Within NPOESS, NOAA is responsible for satellite operations, the Department of Defense is responsible for major acquisitions, and NASA is responsible for the development and infusion of new technologies. In 2000, the NPOESS program anticipated purchasing six satellites for \$6.5 billion, with a first launch in 2008. By November 2005, however, it became apparent that NPOESS would overrun its cost estimates by at least 25 percent, triggering the so-called Nunn-McCurdy review by the Department of Defense.

As a result of the June 2006 Nunn-McCurdy certification of NPOESS,² the planned acquisition of six spacecraft was reduced to four, the launch of the first spacecraft was delayed until 2013, and several sensors were canceled or descoped in capability as the program was refocused on "core" requirements related to the acquisition of data to support numerical weather prediction. "Secondary" sensors that would provide crucial continuity to some long-term climate records, as well as other sensors that would have provided new measurement capabilities, are not funded in the new NPOESS program.³ Costs for NOAA's next generation of geostationary weather satellites, GOES-R, have also risen dramatically, and late last year NOAA canceled plans to incorporate a key instrument on the spacecraft—HES (Hyperspectral Environmental Suite).

¹Note that acronyms not defined in the text, especially those denoting individual instruments and missions, are defined in Appendix D.

²See U.S. House of Representatives Committee on Science, Hearing Charter, "The Future of NPOESS: Results of the Nunn-McCurdy Review of NOAA's Weather Satellite Program," June 8, 2006, available at http://gop.science.house.gov/hearings/full06/June%208/charter.pdf.

³In congressional testimony, the NOAA administrator stated, "Although the primary mission for NPOESS is to provide data for weather forecasting, many of the core sensors mentioned above and some of the secondary sensors would provide some additional climate and space weather observations. Unfortunately, difficult choices and trade-offs had to be made and the cost to procure these sensors is not included in the certified program; however, the program will plan for and fund the integration of these sensors on the spacecraft. Some of these sensors provide continuity to certain long-term climate records while other sensors would provide new data. . . . We specifically decided that the NPOESS spacecraft will be built with the capability to house all of the sensors and the program budget will include the dollars to integrate them on the spacecraft. This decision was made because the [executive committee] agreed any additional funding gained through contract renegotiation or in unutilized management reserve would be used to procure these secondary sensors." Written testimony of Vice Admiral Conrad C. Lautenbacher, Jr. (U.S. Navy, ret.), Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator, "Oversight Hearing on the Future of NPOESS: Results of the Nunn-McCurdy Review of NOAA's Weather Satellite Program," before the Committee on Science, U.S. House of Representatives, June 8, 2006.

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On June 19-21, 2007, the National Research Council (NRC) held a workshop, "Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft," in Washington, D.C., to review options to recover measurement capabilities, especially those related to climate research, that were lost as a result of the Nunn-McCurdy actions and the cancellation of the HES sensor on GOES-R. Some 100 scientists and engineers from academia, government, and industry attended the workshop, which gave participants a chance to review and comment on a mitigation plan developed by NASA-NOAA as well as to explore options that were not included in the NASA-NOAA study. This workshop report summarizes those discussions; by design, it does not present findings or recommendations. A follow-on study that will develop consensus findings and recommendations is underway; a report from that study is scheduled for transmittal on January 31, 2008.

Subjects that were raised repeatedly by workshop participants, and that will be explored in more detail in the follow-on NRC study, include:

- Preservation of long-term climate records. Many participants noted that the demanifesting of climate sensors from NPOESS has placed many long-term climate records at risk, including multidecadal records of total solar irradiance, Earth radiation budget, sea surface temperature, and sea ice extent. Some of these most fundamental data records require observational overlap to retain their value and require immediate attention to ensure their continuation. To ensure continuity of critical long-term climate measurements, many participants also stressed the need to pursue international partnerships and, when feasible, the leveraging of foreign Earth observation missions.
- The potential benefits of relatively minor and low-cost changes to the NPOESS program. In several cases, a workshop participant suggested small nonhardware changes to NPOESS that could address areas of climate interest. Such changes included improving prelaunch characterization and documentation of all NPOESS instruments, adding minor software improvements to the Visible/Infrared Imager/Radiometer Suite (VIIRS)⁴ to make the data more climate-relevant, and downlinking full-resolution spectral data from the Cross-track Infrared Sounder (CrIS)⁵ to enable creation of additional climate products.
- The potential role of spacecraft formation flying in mitigation strategies. Formation flight can allow for the synergistic combination of measurements from multiple satellites, sometimes launched years apart. To allow for subsequent formation flight with NPOESS platforms, some participants suggested consideration of the requisite orbit maintenance and operations requirements as part of the mitigation strategy for restoring deleted NPOESS and GOES-R climate-observing capabilities.
- Mitigation options beyond changes to NPOESS. While particular long-term records can be secured via the remanifesting of certain sensors onto NPOESS, many workshop participants noted that requirements for several could not be addressed even with the original suite of NPOESS instruments. Long-term records of sea level and ocean vector winds, for example, require different orbits and/or instruments to address critical climate observation needs. As a result, some participants heavily favored dedicated altimetry and scatterometry missions to fill this need. Further, some participants noted the critical importance of hyperspectral sounder measurements to climate science, suggesting restoration of CrIS/ATMS to the early-morning NPOESS orbit as well as the earliest-possible flight of a geostationary hyperspectral sounder to further improve temporal resolution.
- The challenge of creating climate data records. Although NPP- and NPOESS-derived environmental data records (EDRs) may have considerable scientific value, climate data records (CDRs)⁶ are far more than a time series of EDRs. Many participants at the workshop emphasized the fundamental differences between products that are generated to meet short-term needs (EDRs) and those for which consistency of processing and reprocessing

⁴VIIRS collects visible/infrared imagery and radiometric data. A key sensor on the NPOESS spacecraft, VIIRS contributes to 23 environmental data records (EDRs) and is the primary instrument associated with 18 EDRs. See description at http://www.ipo.noaa.gov/Technology/viirs_summary.html

⁵In conjunction with the Advanced Technology Microwave Sounder (ATMS), the Cross-track Infrared Sounder collects atmospheric data to permit the calculation of temperature and moisture profiles at high temporal (~daily) resolution. See discussion at http://www.ipo.noaa.gov/Technology/cris summary.html.

⁶See NRC, Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites, National Academy Press, Washington, D.C., 2000, and NRC, Climate Data Records from Environmental Satellites: Interim Report, The National Academies Press, Washington, D.C., 2004.

over years to decades is an essential requirement (CDRs). Creation and maintenance of CDRs require algorithms, data-handling systems, calibration/validation, archival standards, access protocols, and prelaunch characterization that are different from those for operational data products.

- The specifications of the MIS instrument. The specifications of the MIS (Microwave Imager and Sounder) instrument on NPOESS, which is to replace the now canceled CMIS (Conical Microwave Imager and Sounder) instrument, were not known at the time of the workshop. Thus, participants were unable to fully analyze mitigation options. In addition, several participants warned about the consequences of not having an all-weather sea surface temperature retrieval capability, emphasizing the importance of retaining a low-frequency 6.9 GHz channel as the instrument is reconsidered.
- Sustaining climate observations. In the view of many participants, the loss of climate observations from NPOESS is of international concern and also imperils U.S. climate science leadership. Further, many participants noted that discussions at the workshop were focused on solving near-term climate measurement continuity issues, but that there would remain a longer-term problem of sustaining support for climate science. Issues noted included finding an appropriate balance between new and sustained climate observations and managing infusion of technology into long-term observational programs (including the challenges of doing so with a multispacecraft—block-buy—procurement). Workshop discussions also included what many participants cited as a key challenge: accommodating research needs within an operational program. Some participants argued that the relative priority of climate measurement needs would have to be heightened across the implementing agencies if climate and operational weather functions remain combined. Their concern was that in exploiting the commonalities of weather and climate observations, the unique needs of climate scientists would be overlooked. The perceived lack of attention to climate science needs within the Integrated Program Office, particularly calibration and validation requirements, led many participants to favor free-flyer options over integration with the NPOESS platforms.

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Implications of the NPOESS Nunn-McCurdy Certification and the Descoping of GOES-R

Since the 1960s, the United States has operated two separate operational polar-orbiting meteorological satellite systems: the Polar-orbiting Operational Environmental Satellite (POES) series managed by NOAA, and the Defense Meteorological Satellite Program (DMSP) managed by the Air Force. These satellites obtain environmental data that are processed to provide graphical weather images and specialized weather products. These satellite data are also the predominant input to numerical weather prediction models, which are a primary tool for forecasting weather 3 or more days in advance—including forecasting the path and intensity of hurricanes. The weather products and models are used to predict the potential impact of severe weather so that communities and emergency managers can help to prevent or mitigate its effects. Polar satellites also provide data used to monitor environmental phenomena, such as ozone depletion and drought conditions, as well as data sets that are used by researchers for a variety of studies such as climate monitoring.

The history of the NPOESS program and events leading to its restructuring as part of the June 2006 Nunn-McCurdy certification can be found in a recent report by the Government Accountability Office. In June 2006, the Department of Defense (with the agreement of both of its partner agencies, NOAA and NASA) certified a restructured NPOESS program, estimated to cost \$12.5 billion through 2026. This decision approved a cost increase of \$4 billion over the prior approved baseline cost and delayed the launch of the NPOESS Preparatory Project (NPP) mission and the first two NPOESS satellites. Current estimates have the launch of the NPP spacecraft slipping approximately 3 years to January 2010 and the launch of the first and second spacecraft in the NPOESS series, C1 and C2, slipping approximately 3 years to January 2013 and January 2016, respectively. The new program also reduced the number of satellites to be produced and launched from six to four, and reduced the number of instruments on the satellites from 13 to 9—consisting of 7 environmental sensors and 2 subsystems. The number of satellite orbits was also reduced from three to two, with the NPOESS satellite orbiting in the early morning and afternoon positions and the European MetOp satellites being relied on for midmorning orbit data. Figures 1.1 and 1.2 show NPOESS spacecraft, instruments, and orbits prior to and following the Nunn-McCurdy actions.³

Note that acronyms not defined in the text, especially those denoting individual instruments and missions, are defined in Appendix D.

²United States Government Accountability Office, *Polar-orbiting Operational Environmental Satellites: Restructuring Is Under Way, but Challenges and Risks Remain,* GAO-07-910T, U.S. Government Printing Office, Washington, D.C., 2007. Available at http://www.gao.gov/cgi-bin/getrpt?GAO-07-910T.

³NOAA-NASA, "Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals," draft white paper, January 8, 2007.

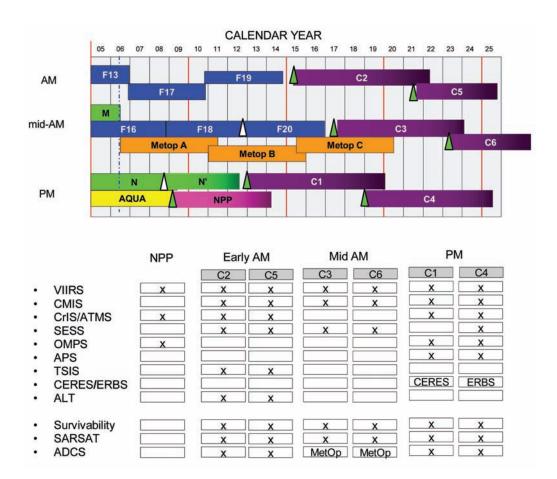


FIGURE 1.1 NPP and NPOESS program summary prior to the June 2006 Nunn-McCurdy program review and revisions. With the exception of CrIS, ATMS, and SESS, all key operational instruments, including SARSAT and ADCS, were intended to be flown on all three orbits. Climate and research-oriented sensors were generally designated a spot on a single satellite at any one time. The overall NPOESS constellation was designed as a stand-alone system, with the European series of MetOp satellite viewed as a separate, independent, complementary system. SOURCE: Courtesy of NOAA.

The Nunn-McCurdy process placed priority on continuity of operational weather measurements. Box 1.1 summarizes the effects of the Nunn-McCurdy action on previous objectives related to climate research.

HES CANCELLATION AND GOES-R

With the final two GOES satellites in the current GOES-N series completed, NOAA is now in the early stages of the acquisition process for the next generation of GOES satellites, called GOES-R. Late in 2006, NOAA announced the cancellation of plans to include the Hyperspectral Environmental Suite (HES)⁴ on GOES-R. At a

⁴For a description of HES, see T.J. Schmit, J. Li, and J. 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.

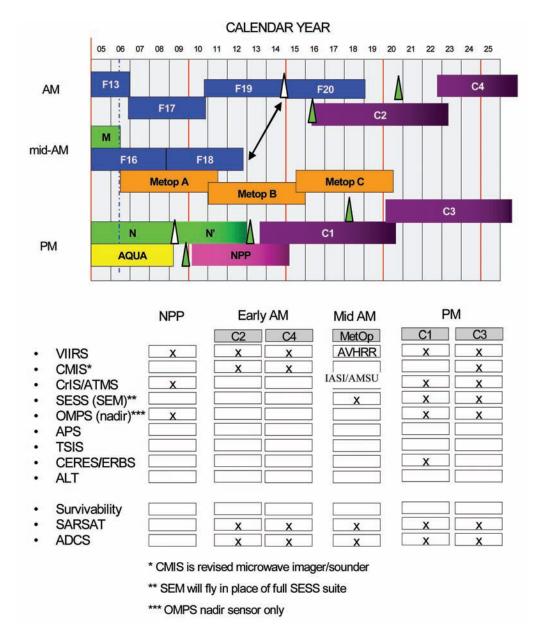


FIGURE 1.2 NPP and NPOESS program summary following the Nunn-McCurdy program review and revisions (status as of October 2006). The midmorning satellite coverage will be provided by the European MetOp satellite series, with descoped NPOESS satellites covering the early morning and afternoon orbits. Instruments removed from the core NPOESS program plan can be integrated and flown if outside funding will support the remaining development costs, as well as the cost of the instrument and its support. The canceled Conical Microwave Imager and Sounder sensor will be replaced by a sensor now called the Microwave Imager and Sounder (MIS). Although its specifications are not yet known, by design MIS will be a less expensive instrument with less developmental risk. SOURCE: Courtesy of NOAA.

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BOX 1.1
Summary of Effects of Nunn-McCurdy NPOESS Certification

- · Priority placed on continuity of operational weather measurements
- · Number of orbits and spacecraft reduced
 - -Before Nunn-McCurdy: 3 orbits and 6 spacecraft
 - -After Nunn-McCurdy: 2 orbits and 4 spacecraft
- Impacts on climate sensors
 - —Five climate-oriented sensors demanifested
 - APS (aerosols), TSIS (solar irradiance), OMPS-Limb (ozone), ERBS (radiation budget), ALT (ocean altimetry)
 - · Instruments flown only if developed outside of NPOESS program
 - —Three climate-oriented sensors have reduced coverage
 - VIIRS (imagery), CrIS (thermal sounder), ADCS (data relay)
 - Reduced diurnal coverage due to reduction in orbits used (VIIRS and ADCS) and demanifesting
 of CrIS from early-morning orbit
 - —One climate-oriented sensor will have reduced capability
 - CMIS (microwave sounder)
 - · Less expensive, less capable instrument of the same type

SOURCE: Adapted from J. Privette, J. Bates, and T. Karl, "Climate Goal Impacts and Possible Mitigations with a Certified NPOESS," presentation at Polar Max 2006, available at http://www.npoess.noaa.gov/polarmax/2006/day03/4.5Privette_revised_NPOESS.Climate.POLARMAX.ppt.

September 2006 hearing of the U.S. House of Representatives Committee on Science and Technology, NOAA Administrator Conrad C. Lautenbacher explained:⁵

At first, we envisioned GOES-R as a satellite series that would contain significant technological advancements. . . . The Hyperspectral Environmental Suite (HES) was conceived as an advanced sounder and coastal water imager that would provide a profile of atmospheric temperature and moisture content used in weather forecasting and take images of coastal areas for water quality monitoring and coastal hazard assessment. . . . While HES potentially could have provided a major improvement in our ability to characterize the atmosphere and the coastal environment, we did not think it was prudent to accept that much risk in an operational satellite for an acquisition program. We are examining alternate ways to maintain today's sounding capability for GOES-R. . . . Fulfilling the coastal waters component of the sounder capability remains a NOAA priority.

Although most of the June 2007 workshop focused on recovery options for the demanifested and descoped climate sensors on NPOESS, sessions were also held to discuss recovery options for HES, including a potential role for the GIFTS instrument.⁶

⁵Written testimony of Vice Admiral Conrad C. Lautenbacher, Jr. (U.S. Navy, Ret.), Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator, Oversight Hearing on the Government Accountability Office Report on NOAA's Weather Satellite Program Before the Committee on Science, U.S. House of Representatives, September 29, 2006, available at http://www.legislative.noaa.gov/Testimony/lautenbacher092906.pdf.

⁶Developed under NASA's New Millennium Program, the Geosynchronous Imaging Fourier Transform Spectrometer (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. GIFTS was intended to serve as a major element in risk reduction plans for GOES-R. Because

THE NASA-NOAA STUDY

Shortly after the June 2006 announcement of the certified NPOESS program, the White House Office of Science and Technology Policy requested that NASA and NOAA study the climate science impacts attributable to the instrument deletions and scope reductions. Presentations by agency officials at the panel's June 2007 workshop were effectively the starting point for many of the workshop's discussions. In particular, "Mitigation Approaches to Address Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals," reproduced as Appendix C, provided essential background information.

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. See W.L. Smith et al., "The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS)," pp. 700-707 in *Proceedings of the 11th Conference on Satellite Meteorology and Oceanography*, Madison, Wisc., October 15-18, 2001 (preprints), Call Number Reprint # 2999, American Meteorological Society, Boston, Mass., 2001, available at http://ams.confex.com/ams/pdfpapers/71904.

⁷All presentations, as well as summaries of the workshop sessions, are available at http://www7.nationalacademies.org/ssb/SSB_NPOESS2007_Presentations.html.

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Summary of the Workshop Sessions

The workshop's breakout sessions were designed to have participants consider the impact of changes to the NPOESS and GOES-R programs from many different perspectives. On day 1 of the workshop, participants considered impacts in terms of their effects on the measurement of essential climate variables (ECVs), as specified by the GCOS Implementation Plan. On day 2, impacts were considered in terms of the specific sensors that constituted the original programs' baselines. The panel recognized that there would be overlap in these discussions, but thought it useful for participants to consider the broad issues of ECV measurement and development of climate data records (CDRs) apart from specific concerns about NPOESS sensors. Day 3 breakout discussions were more loosely organized, to allow for broad discussion of cross-cutting issues, long-term considerations critical to the production of CDRs, and the advance of climate science in general. Indeed, a recurring theme expressed by many participants at the workshop was that ensuring the measurement(s) of a particular climate variable(s) was only a necessary first step toward enabling the creation of time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change, that is, to generate CDRs (see "Panel on Issues Related to CDR Development," p. 39).

WORKSHOP SUMMARY—DAY 1

The day 1 breakout groups were charged to consider, as a community, the various ECVs that might be affected by the Nunn-McCurdy NPOESS and GOES-R descopes. Participants considered each NPOESS-measured parameter, starting with ones in jeopardy of not meeting Integrated Operational Requirements Document (IORD) specifications, commenting on the relevance of the parameter to climate science and/or long-term climate records, the importance of maintaining the IORD-level value (and potential consequences if it is not met), and noting any additional considerations required to make the NPOESS program's environmental data records (EDRs) more relevant to GCOS ECV climate parameters and to the climate community as a whole (e.g., additional instrument characterization, calibration, overlap requirements). Participants were also encouraged to suggest mitigation approaches where NPOESS current plans fall short of climate community needs, and to assess whether any of the missions recommended in the Earth science decadal survey² might enable recovery of the NPOESS climate

¹The GCOS Implementation Plan (GCOS-107) is available at http://www.wmo.int/pages/prog/gcos/ Publications/gcos-107.pdf.

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

measurements. Participant feedback on each of these areas was captured in real time in a template,³ and a brief summary of the discussions is provided here.

Consideration of NPOESS and GOES-R Priority Measurements for ECVs— Breakout Sessions

Climate Data Records Related to Observations of the Atmosphere

The atmosphere ECV breakout group was asked to consider 10 ECVs related to observations of the atmosphere: Earth radiation budget (including solar irradiance); aerosol properties; ozone; carbon dioxide, methane, and other greenhouse gases; cloud properties; precipitation; water vapor; surface wind speed and direction; upperair wind; and upper-air temperature. Recognizing the linkages between the ECVs, the group organized itself into four subgroups:

- Radiation budget (Earth radiation budget, aerosol properties),
- Ozone and trace gases (ozone; carbon dioxide, methane, and other greenhouse gases),
- Clouds and precipitation and water vapor (cloud properties, precipitation, water vapor), and
- Winds and temperature (surface wind speed and direction, upper-air wind, upper-air temperature).

A summary of the discussions is provided here, organized according to ECV.

Earth Radiation Budget (Including Solar Irradiance)

Persistent small climate changes are difficult to detect within the diurnal, regional, and seasonal variance of Earth's reflected (shortwave) and emitted (longwave) energy—hence a continuous long-term (decades) record of Earth's radiation budget (ERB) is needed to identify subtle long-term shifts related to climate change. With the demanifesting of TSIS and ERBS from NPOESS, ERB measurements will end with the last CERES on Aqua (or perhaps NPP, pending addition of CERES FM-5 onto NPP), the TIM record will end with Glory, and the SIM record with SORCE. Planned or proposed international missions and instruments of relevance include EarthCARE, ScaRAB on Megha-Tropiques, and GERB; however, in the view of breakout participants who commented on them, these international missions are insufficient to maintain the ECVs. The Earth science decadal survey recommended that NOAA add CERES to NPP and that NASA develop CLARREO, which would provide spectral ERB measurements. It was noted that ERBS (Earth radiation budget sensor) needs VIIRS cloud imagery, and so flight near NPOESS was desirable. SIM and TIM could be on separate spacecraft from ERBS since they are Sun pointing.

Aerosol Properties

Measurement of aerosol properties is needed to understand the global distribution of aerosols and their impact on Earth's energy balance, clouds, and precipitation. Aerosol impacts remain a source of major uncertainty in climate prediction in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (2007).⁵ Recent and ongoing missions and instruments providing aerosol information include TOMS (1979-), AVHRR (1979-), MODIS (1999-), MISR (1999-), POLDER (2002-), (A)ATSR (1991-), PARASOL (2006-), SCIAMACHY (2003-), CALIPSO (2006-), GLAS (2003-), OMI (2004-), and AIRS (2002-). International missions of relevance include EarthCARE, GCOM-C/SGLI, ADM/Aeolus, and ATLID. The upcoming NASA Glory mission will fly APS, which was originally intended to be followed by subsequent NPOESS flights of APS to provide a continuing data record. With the demanifesting of APS from NPOESS, some aerosol information will be obtained through

³The filled-in templates are available at http://www7.nationalacademies.org/ssb/SSB_NPOESS2007_Presentations.html.

⁴See, for example, NRC, Solar Influences on Global Change, National Academy Press, Washington, D.C., 1994.

⁵Intergovernmental Panel on Climate Change, *Climate Change 2007*, IPCC Fourth Assessment Report, Cambridge University Press, Cambridge, U.K., 2008, available at http://www.ipcc.ch/ipccreports/assessments-reports.htm.

VIIRS, OMPS, and CrIS/ATMS; however, these instruments will not provide polarimetry information. Workshop participants noted that the ACE mission, as described in the Earth science decadal survey, would provide significant advances. Attendees expressed a strong desire to move to a next-generation polarimeter rather than lock in to the technology of APS, as would have been required for accommodation on NPOESS. The 3D-Winds mission recommended in the decadal survey would provide aerosol heights, which would also contribute to measurement of the properties of this ECV.

Ozone

The ozone ECV is important to monitoring the long-term trends in surface ultraviolet (UV) radiation and recovery of the ozone layer. The ozone ECV is at risk due to the demanifesting of OMPS-Limb by the NPOESS program, although it has recently been restored to the NPP platform. After NPP, no ozone profile measurement is currently planned as part of NPOESS, which after the Nunn-McCurdy action carries only the OMPS-Nadir portion of the original suite. Ongoing missions and instruments of relevance to the ozone ECV include TOMS (1979-), SBUV (1979-), GOME (2006-), MIPAS (2003-), OMI (2003-), SCIAMACHY (2003-), TES (2005-), GOME-II (2006-), MLS (2004-), AIRS (2002-), and IASI (2006-). The decadal survey recommendation for GACM was considered relevant to the ozone ECV, although it was recommended for launch after 2016. In the breakout session, several participants noted that the NPOESS nadir ozone measurement (which is the only ozone measurement to be made by NPOESS) is more than adequately covered by GOME-II on MetOp and that ozone profile measurements would add more value than additional nadir measurements.

Carbon Dioxide, Methane, and Other Greenhouse Gases

Measurements of key greenhouse gases, including CO₂ and CH₄, are essential parts of a program to understand climate forcings and trends. Indeed, measurements are needed with sufficient quality to detect sources and sinks at regional scales. The NPOESS CrIS instrument will contribute to this ECV, and some breakout participants noted that its value would be increased if all the spectra were downlinked. Ongoing missions and instruments related to the greenhouse gases ECV include IRS (2002-), SCIAMACHY (2003-), MIPAS (2003-), HIRDLS (2004-), MLS (2004-), TES (2004-), GOME-II (2006-), and IASI (2006-). AIRS and IASI both currently produce midtroposphere CO₂ data products, although both remain to be validated. NASA's planned OCO mission (scheduled for launch late in 2008) and the JAXA GOSAT mission will also contribute to the CO₂ measurement needs for this ECV. The decadal-survey-recommended ASCENDS mission is also of interest. Some workshop participants noted the desirability of a GIFTS- or HES-like instrument for geostationary measurements (with high temporal resolution) relevant to this ECV.

Cloud Properties

Ongoing missions and instruments of relevance to the cloud properties ECV include AVHRR/HIRS (1978-), (A)ATSR (1991-), MODIS (2000-), MISR (1999-), AIRS (2002-), SEVIRI (2003-), GOES (1994-), METSAT (2004-), MTSAT-1R (2005-), IASI (2006-), CloudSat (2006-), and CALIPSO (2006-). On NPOESS, contributions include VIIRS (which includes a day and a night imager) and CrIS/ATMS (and, prior to the Nunn-McCurdy action, APS). Planned missions/instruments of relevance include GLM and EarthCARE. The cloud properties ECV can be significantly advanced via the ACE mission recommended by the Earth science decadal survey, which would investigate aerosol-cloud interactions.

Precipitation

The water cycle plays a critical role in climate change. Precipitation measurements are key to understanding and predicting water vapor feedback, water supply, drought, severe storms, and floods. Ongoing missions and instruments of relevance to precipitation measurement include SSM/I (1987-), TMI (1997-), AMSR-E (2002-),

TRMM (1997-) CloudSat (2006-), MODIS (1999-), and AIRS (2002-) (the last two provide important information on clouds and water vapor). NASA's upcoming GPM mission is of great relevance to this ECV. International plans for GCOM-W and AMSR F/O (2011) are also of interest. Participants discussed the relevance of the decadal survey's recommended ACE and PATH missions, which would provide important information on aerosol-cloud interactions and high-temporal-resolution precipitation, respectively. NPOESS CrIS/ATMS measurements will contribute to the precipitation ECV, but questions remain about the still-undefined MIS capability. Some participants expressed concern that a capability for passive microwave precipitation measurements may not emerge in the revised MIS sensor, and they suggested that NPOESS place emphasis on the water cycle (water vapor, liquid water, ice water, and precipitation) when considering MIS requirements, possibly including giant magneto-impedance (GMI) bands.

Water Vapor

With measurements available through CrIS/ATMS on NPOESS, IASI on MetOp, and ABI on GOES-R, there was little concern expressed about the water vapor ECV. MIS capabilities, still uncertain, should include total column water vapor information. Several participants suggested that the water vapor channel be added back to VIIRS to further strengthen the water vapor ECV, while also benefiting wind and aerosol measurements. Ongoing missions and instruments of relevance include SSM/I (1987-), SSMIS (2003-), (A)ATSR (1991-), AMSR-E (2002-), MERIS (2002-), HIRS (1979-), AIRS/AMSU (2002-), MODIS (1999-), TMI (1997-), and MLS (2004-). International plans include GCOM-W and AMSR F/O (2011). Decadal survey missions of relevance include GPS/RO and PATH.

Surface Wind Speed and Direction

Measurements of surface wind speed and direction are needed for both climate and operational purposes. For climate, vector winds are required to compute wind stress curl, an essential climate quantity that drives Ekman pumping and suction in the ocean, thereby implying vertical circulations (i.e., upwelling and downwelling). The zonal integral (east to west) of wind stress curl across an ocean basin is proportional to the western boundary current transport (i.e., the transport responsible for the dominant part of the poleward heat flux by the ocean). The climatology of storms (frequency and intensity) depends on vector wind measurement, and measurements are required in all conditions. Several participants noted that the CMIS replacement (MIS) is not expected to meet needs for data on these variables. Several participants also noted that the NPOESS key performance parameter is wind speed only, and so measurement of wind direction is not ensured as trade-offs are explored. Ongoing missions and instruments of relevance to this ECV include QuikSCAT (1999-), ERS (1992-), and WindSat (2003-). The international ASCAT⁶ measurement and the decadal survey recommendation for XOVWM were also discussed. Participants engaged in a lively debate over the relative merits of passive versus active measurement of surface wind speeds; they also discussed the merits of a future system that would combine the active measurement capabilities of ASCAT with the passive measurements to be provided by MIS. It was the strongly held view of many workshop participants that ASCAT and MIS would be inadequate to meet both operational and climate needs, and that an additional active surface wind speed and wind direction measurement was needed. This ECV was also considered by the oceans breakout group and is further discussed in the summary of its session below.

Upper-Air Wind

Three-dimensional upper-air wind, temperature, and moisture profiles with high vertical and temporal resolution are key to improved prediction of hurricane track and intensity. The upper-air wind ECV is at moderate risk due to its partial reliance upon both NPOESS/VIIRS (which lacks the water vapor band needed to continue MODIS

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⁶The ASCAT scatterometer is an active instrument; however, it does not provide the wide swath coverage or resolution afforded by QuikSCAT.

measurements of polar winds) and GOES-R/HES (for continuous full-disk four-dimensional wind vertical profiling, including diurnal coverage). GOES-R/ABI will provide cloud wind tracking and measurements of clear-sky water vapor layer-integrated winds, including diurnal coverage. Ongoing missions and instruments of relevance to the upper-air wind ECV include AVHRR (1979-), MODIS (1999-), (A)ATSR (1991-), GOES (1975-), Meteosat (1978-), GMS (1980s-), Feng Yun (2000s-), and INSAT (2000s-). The international ADM/Aeolus mission is relevant to this ECV, as is the 3D-Winds mission recommended by the Earth science decadal survey.

Upper-Air Temperature

The upper-air temperature ECV appears to be in good health with the planned flight of CrIS/ATMS on NPOESS and IASI on MetOp, although several participants noted that the inadequate diurnal coverage could be improved by addition of CrIS to the early AM (0530, descending) NPOESS spacecraft. Ongoing missions and instruments of relevance to the upper-air temperature ECV include MSU (1979-), AMSU (1999-), CHAMP (2001-), COSMIC (2006-), GRAS (2006-), HIRS (1979-), and AIRS (2002-). The decadal survey recommendations for GPS/RO, CLARREO, and PATH are also considered relevant to this ECV. Some participants noted that a geosynchronous Earth orbit (GEO) flight of opportunity to fly GIFTS or another Pathfinder could further recover ability to observe and integrate upper-air temperature across the diurnal cycle.

The breakout group also discussed air quality observation needs, though noted that air quality is not currently a GCOS ECV.

Climate Data Records Related to Observations of the Oceans

The oceans ECV breakout group was tasked to consider six ECVs related to ocean observations: sea level, SST, ocean color, salinity, sea state, and sea ice. Some participants also noted the need for ocean measurement input to several atmospheric ECVs (surface wind speed and direction, precipitation, surface radiation, surface air temperature, and water vapor). A summary of the discussions is provided below, organized according to ECV.

Sea Level

The 15-year record of sea surface height has provided a record of global sea level rise, built on TOPEX and Jason-1 data records. Discussions at the breakout focused on measures to ensure the continuity of this record, a strong desire among most participants. Ongoing missions and instruments of relevance include Jason-1, ENVISAT, and GFO. NASA plans include a Jason follow-on, the Ocean Surface Topography Mission (OSTM)/Jason-2. There are international plans for an accurate altimeter aboard the European Sentinel-3,7 although it will suffer from tidal aliasing due to a Sun-synchronous orbit. The decadal survey recommendation for a NASA advanced altimetry mission called SWOT is also of key interest. Altimeters on NPOESS could help to provide global coverage and measure ocean heat content. However, the removal of the altimeter from NPOESS is not considered a critical issue for climate, as ALT would not have provided a climate-quality sea surface height record due to the NPOESS Sun-synchronous orbit, nor would it have provided information about inland waters and near-coastal areas. For measurements related to the needs of climate researchers, most breakout participants expressed a preference for free-flyer missions that achieve the same quality as Jason, either as a series of Jason follow-on missions such as Jason-3 followed by SWOT, or as a series of SWOT missions, started by advancing the timeline for the first SWOT mission.

⁷For information on the European Space Agency's planned Sentinel series, see http://www.esa.int/esaLP/SEMZHM0DU8E_LPgmes_0.html.

Sea Surface Temperature

Remote sensing of sea surface temperature (SST) has a long heritage, dating back to 1980. Climate studies require all-weather SST coverage, involving complementary infrared (IR) and microwave observations. IR observations provide high spatial resolution and radiometric fidelity in clear skies, and microwave observations provide SST measurements in the presence of clouds and aerosols. Ongoing missions and instruments of relevance include AVHRR (1979-), (A)ATSR (1991-), Aqua/AMSR-E (2002-), MSG/SEVIRI, GOES imagers, TRMM/TMI, TRMM/VIRI, and Aqua/Terra MODIS (1999-). International plans include OceanSat-1 and -2, Sentinel-3 series (2013-2020), MetOp (B, C, D), GCOM-C, and GCOM-W/AMSR-2. The decadal survey PATH mission is also of interest. On NPOESS, MIS will replace the canceled CMIS (but currently is not slated for inclusion until the second NPOESS spacecraft launches in 2016). Of particular concern to many workshop participants was the expectation that the certified NPOESS MIS configuration will lack the desired band for passive microwave SST (6.9 GHz), which would create a gap in the SST record. Many participants also suggested the need for sustained daily global coverage of the IR observations. Continuity of both IR and passive microwave SST observations on polar and geostationary platforms was considered by many participants to be essential for an accurate and robust SST CDR, as also noted by the International GHRSST-PP science team. Continuity by CMIS/MIS with current AMSR-E observations remains a major concern.

Ocean Color

Tracking of trends in ocean productivity via remote sensing of ocean color is an important aspect of ocean climate study. Measurements of water-leaving radiances are needed, and some participants expressed a desire for a more comprehensive approach than observation and monitoring of chlorophyll. Ongoing missions and instruments of relevance include SeaWiFS (1997-), MERIS (2002-), and Aqua/MODIS (2002-). International plans for OceanSat-2, Sentinel-3, and GCOM-C/SGLI are also of interest, as is the ACE mission recommended by the decadal survey. Ocean color measurements were to be provided by NPOESS/VIIRS and GOES-R/HES. The ocean color ECV is considered at risk due to removal of HES from GOES-R. Ocean color scientists noted that the NPOESS platform and its VIIRS sensor will not be satisfactory for ocean color science, in part because NPOESS does not provide for lunar calibration of VIIRS and in part because of VIIRS hardware issues involving increased optical cross-talk.⁹ Ocean color researchers at the workshop asserted that observations should have band coverage ranging from UV to shortwave, and they suggested modifying the GCOS ECV to include ocean color records beyond chlorophyll. The ocean biology scientists who were present suggested development of a dedicated ocean biology sensor and mission to accommodate the need for lunar calibration, building on the approach taken by the SeaWiFS instrument. In situ calibration with ocean buoys is also an important consideration.

Salinity

Measurement of sea surface salinity is a new capability. The European Soil Moisture and Ocean Salinity (SMOS) mission and the NASA Aquarius mission will provide the first satellite sensing of sea surface salinity (which will require measurements of surface wind speed and SST as part of the retrieval process). There is as yet no satellite climate record to evaluate the results of these missions.

⁸For information on the Global High-Resolution Sea Surface Temperature Pilot Project, see http://ghrsst-pp.org.

⁹In remote sensing, optical cross-talk is an important error source that results when a detector responds to impinging light from out-of-channel wavelengths (e.g., due to scattering, internal reflections, or other optical leaks). This out-of-channel component of the detector signal can be difficult or impossible to de-convolve with the in-channel (desired) signal. At the time of the workshop, VIIRS was at risk of not meeting the instrument requirement that limits the level of acceptable optical cross-talk. The optical filter assembly in VIIRS, which separates incoming signal into a number of smaller wavelength channels, is known to be the source of the optical cross-talk problem. Efforts are underway to seal light leaks and reduce scattered light. If the VIIRS optical cross-talk issue is not resolved, ocean color and aerosol products will be adversely affected.

Sea State

As winds over the ocean change in response to climate variability and climate change, there will be changes in sea state. The sea state is important for marine weather and for the safety of life at sea, forecasts, and warnings. Some participants questioned whether the sea state ECV represented a fundamental measurement. From a climate perspective, the roughness of the sea surface plays a role in air-sea exchanges. It would be ideal to have full wave directional spectral capability, spanning surface gravity wave and surface swell periods. This is not at present a satellite capability.

Sea Ice

With MIS delayed until NPOESS C2, there is a need to continue the long (28-year) climate data record of sea ice extent and concentration collected by passive microwave radiometers; continued scatterometer and altimeter measurements are also required. Changes in sea ice and ice coverage are a critical indicator of climate change. Ongoing missions and instruments of interest include SMMR, SSM/I (DMSP), SSMIS, AMSR-E, QuikSCAT, MODIS, and ASCAT. Planned missions include the DMSP missions, F19 and F20, carrying SSMIS; GCOM-W/AMSR-2; GCOM-C/SGLI; RADARSAT-2; and CryoSat-2. The decadal survey recommendations for SCLP, ICESat-II, XOVWM, and DESDynI are also of interest. With MIS delayed, a passive microwave data gap is anticipated. A synthetic aperture radar or equivalent capability is also needed in the production of the sea-ice climate data record for validation of sea ice concentration and edge. This could be provided by the XOVWM scatterometer. To fill the gap, a free-flyer QuikSCAT replacement combined with an AMSR-type instrument would be a backup against DMSP failures.

Surface Wind Speed and Direction

From an oceanographic perspective, there is a need for vector wind measurements, and many participants noted that surface vector winds from passive microwave did not fulfill the need for climate-quality surface vector winds and for observation of extreme weather events. Thus, to these participants, the removal of CMIS from NPOESS was not a major issue. Many of the breakout group's participants indicated the real need to enhance climate measurement capabilities beyond the QuikSCAT standard in a follow-on, active radar surface vector wind mission. The QuikSCAT mission has provided an 8-year record to date and has exceeded its design lifetime. Follow-on options discussed included relying on ASCAT on MetOp, duplicating QuikSCAT, and flying XOVWM (as recommended by the Earth science decadal survey). The XOVWM option has the advantages that that sensor can measure higher wind speeds than can QuikSCAT, can provide improved vector wind retrievals in rain, and can detect surface rain rate. Higher spatial resolution (~1 km) is also desired. It was also noted that the incremental cost of XOVWM versus a QuikSCAT duplicate would be small, in part because QuikSCAT was designed and developed more than a decade ago.

Precipitation, Surface Radiation, Surface Air Temperature, and Water Vapor

Simultaneous knowledge of the surface forcing of the ocean (heat, water, momentum fluxes from the atmosphere) and ocean-atmosphere exchange is important to monitoring and understanding the ocean's role in climate. Global ocean remote sensing coverage of rainfall, surface incoming and net shortwave and longwave radiation, and latent and sensible heat fluxes is needed. Latent and sensible heat flux can be parameterized given surface wind, SST, and surface air temperature and humidity. The oceanographic community supports collection of climate-quality surface radiation and rainfall fields. It remains a significant challenge to retrieve surface air temperature and surface humidity from space, and existing data are not considered to be of the quality needed to generate CDRs.

Other Discussion

Some participants felt that the requirements to instrument selection process did not sufficiently engage the ocean climate user community, and they expressed a continuing need for this engagement to ensure that the missions flown support collection of climate-quality data records. NASA science teams are one model to ensure such engagement. The science team approach has worked particularly well in terms of federating international activities for several CDRs, including SST (the GHRSST-PP), ocean color (International Ocean Colour Coordination Group (IOCCG)), and altimetry (Ocean Surface Topography Science Team (OSTST)).

Further, some participants noted that for SST, sea ice, and ocean surface vector winds there is possible synergy and an optimum combination for accuracy, data gap limitation, spatial and temporal resolution, and CDR continuity that should be considered. All three of these CDRs would benefit from sensor collocation. A solution would be to pursue XOVWM and AMSR-type sensors on the same satellite or in formation, and in polar orbit. This approach would entail acceleration of the XOVWM schedule. Another approach would be to modify XOVWM to accommodate passive microwave (6.9 GHz) SST with surface wind speed (required for accurate SST retrievals at 6.9 GHz) together with sea ice monitoring. An XOVWM+SST system in low-inclination orbit would enhance studies of tropical weather and climate.

Climate Data Records Related to Observations of the Land

The land ECV breakout group was asked to consider 10 ECVs related to surface observations: glaciers and ice caps/sheets, snow cover, soil moisture, fire disturbance, lakes, biomass, land cover, surface albedo, fraction of absorbed photosynthetically active radiation (FPAR), and leaf area index (LAI).

The primary NPOESS instrument for land surface climate variables is VIIRS, following the heritage of AVHRR and MODIS sensors. Likewise, for GOES the primary land climate instrument will be the imager (ABI on GOES-R). The first hour or so of the breakout addressed the VIIRS and its known problems, primarily concerning optical cross-talk. The cross-talk as it stands now will affect the aerosol EDRs and the land EDRs, the latter primarily through poor aerosol correction. It is not clear that the cross-talk issue for VIIRS will be fixed in time for its first flight on NPP. Although an improved filter is being constructed and is planned for installation, participants were informed that there remains at least a 30 percent chance that the fixes will not work and that the land EDRs will be out of specification.

Participants considered the importance of land ECVs in terms of scientific impact and the availability of longer-term data sets for comparison and study. The land ECVs were then each evaluated in terms of risk. All risk evaluations in this summary assume that the cross-talk issue for VIIRS will be successfully alleviated.

Glaciers and Ice Caps/Sheets

The glaciers and ice caps/sheets ECV is of importance to climate models and albedo, water balance, sea level, and radiation budget climate studies. Ongoing missions/instruments of relevance include Landsat (1984-), SPOT, ASTER (2000-), GRACE (2002-), ICESat, MODIS (1999-), and MISR (2000-). The international Cryosat-2 mission, currently in its implementation phase, and the ICESat-II, GRACE-II, DESDynI, and SCLP missions recommended by the Earth science decadal survey are also relevant. NPOESS' VIIRS is expected to contribute to this ECV; however, there is some risk to the ECV associated with the lack of ALT data required to estimate mass balance, although other altimeter measurements (if secured) can meet the need.

Snow Cover

Measurement of snow cover is a high priority because of snow cover's role in radiation budget and water cycle studies. Ongoing missions and instruments of relevance include AVHRR (originally VHRR; 1972-), MODIS (1999-), (A)ATSR (1991-), Landsat, SPOT, and SSM/I. NPOESS will contribute via VIIRS and ATMS; however, planned contributions by the CMIS replacement, MIS, are now uncertain. The snow cover ECV is also affected because VIIRS data can be used to map areal extent through time but a height/depth-related measure, which is required to make key calculations of mass, is missing. The decadal survey SCLP mission is relevant to this ECV, as it would provide passive and active microwave measurements of snow water equivalent. GOES-R ABI measurements are also of relevance, as are international plans for Sentinel-3.

Soil Moisture

The soil moisture ECV is important to climate science due to its impact on biogeochemical cycling, meso-scale climate models, vegetation dynamics, albedo, and surface roughness. Ongoing missions and instruments of relevance include AMSR-E (2002-), ALOS (2006-), Landsat, MODIS (1999-), and ASCAT (2006-). The planned NASA LDCM mission and international SMOS missions are also of interest. The NPOESS VIIRS and CMIS instruments are relevant to soil moisture; however, the soil moisture ECV is considered at high risk due to the CMIS descope, which effectively eliminates any possibility of retrieving this measurement. Even with CMIS, soil moisture measurements would have been limited to bare or very sparsely vegetated soils. Recommended by the Earth science decadal survey, SMAP, an active and passive L-band mission to directly measure soil moisture, would provide direct global soil moisture measurements with greater penetration depth.

Fire Disturbance

The fire disturbance record has climate science implications in terms of understanding biogeochemical cycling, disturbance, and disasters. Ongoing missions and instruments of relevance include AVHRR (1982-), (A)ATSR (1991-), SPOT (1998-), Landsat, ASTER, MODIS (1999-), and MERIS (2002-). International plans for GCOM-C/SGLI (2012-2025) and Sentinel-2 are also of interest. VIIRS on NPOESS and ABI on GOES-R are expected to contribute to this ECV; however, there is a moderate risk to the ECV due to the low saturation level of the VIIRS instrument and the lack of VIIRS in a midmorning orbit. The saturation issue prevents the retrieval of fire radiative power, ¹⁰ which is an important component of this ECV, and the loss of the midmorning orbit reduces the measurement of fire diurnal cycles.

Lakes

The lakes ECV is of relevance to biogeochemical cycling, eutrophication, mesoscale climate models, human impact, vegetation dynamics, water cycle, and radiation budget climate studies. Ongoing missions and instruments of relevance include ERS-2/AATSR (1995-), MERIS (2002-), SeaWiFS (1997-), Jason-1 (2001-), Landsat (Landsat-7, 1999-), SPOT (SPOT-5, 2002-), and AVHRR (on NOAA POES). NASA plans for OSTM/Jason-2 and LDCM, international plans for Sentinel-3 and GCOM-C/SGLI, and the decadal survey recommendation for SWOT are also of interest. NPOESS/VIIRS can address the surface area of lakes; however, there remains a lack of three-dimensional measurement capability.

¹⁰It has been demonstrated in small-scale experimental fires that the amount of radiant heat energy liberated per unit time (the fire radiative power; FRP) is related to the rate at which fuel is being consumed. This is a direct result of the combustion process, whereby carbon-based fuel is oxidized to CO₂ with the release of a certain heat yield. Therefore, measuring this FRP and integrating it over the lifetime of the fire provides an estimate of the total fire radiative energy (FRE), which for wildfires should be proportional to the total mass of fuel biomass combusted. See M.J. Wooster, G. Roberts, G.L.W. Perry, and Y.J. Kaufman, "Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release," *Journal of Geophysical Research* 110:D24311, doi:10.1029/2005JD006318, 2005.

Biomass

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Measurements of biomass are important to studies of biogeochemical cycling, modeling, mesoscale climate models, human impact, vegetation dynamics, and surface roughness. Ongoing missions and instruments of relevance include ALOS/PALSAR (2006-), ENVISAT/ASAR, Landsat, MODIS (1999-), MERIS (2002-), ICESat, and ASTER. NASA plans for LDCM, international plans for Cryosat-2, ALOS, and ESA-BIOMASS, and the decadal survey recommendations for DESDynI and ICESat-II are also of interest. NPOESS/VIIRS is expected to contribute to this ECV; however, there remains a lack of three-dimensional measurement capability (e.g., from lidar or radar).

Land Cover, Surface Albedo, Fraction of Absorbed Photosynthetically Active Radiation, and Leaf Area Index

The above ECVs are important to climate studies due to their role in biogeochemical cycling, modeling, meso-scale climate models, human impact, vegetation dynamics, albedo, and surface roughness. Ongoing missions and instruments of relevance include AVHRR, MODIS (1999-), (A)ATSR (1991-), Landsat, SPOT, MERIS (2002-), GLI, ASTER, MISR (2000-), GOES, MSG, and POLDER. The NASA-planned LDCM mission, the international plans for Sentinel-3 and GCOM-C/SGLI, and the decadal survey recommendation for HyspIRI are also of interest. These ECVs are considered to be at low risk because they can be adequately addressed by VIIRS (assuming cross-talk is mitigated). If the VIIRS cross-talk issue is not resolved, there will be moderate risk to these ECVs.

WORKSHOP SUMMARY—DAY 2

The breakout groups on day 2 focused on the impacts of NPOESS and GOES-R descopes sensor by sensor. Participants were asked to comment on the various mitigation options suggested by NASA and NOAA presenters on day 1 and to suggest other mitigations to recover lost capabilities of importance to the climate community. Where appropriate, participants also considered whether missions in the Earth science decadal survey mission set might enable the recovery of the NPOESS climate measurements. ¹¹ As on day 1, templates were filled in during the breakout sessions, and they are available online. ¹² After the workshop a short background section was added to each breakout session summary to provide context for the discussions. *It is important for the reader to recognize that the mitigation options presented below do not include all that might be considered and that both the options and the analysis are necessarily the subjective and not always disinterested views of presenters and participants.*

Breakout Sessions

Radiation Sensor Measurements

Background

TSIS, ERBS, and OMPS-Limb measure, respectively, the incoming solar energy, the energy reflected and emitted by Earth, and the height-dependent concentration of atmospheric ozone that modulates these energy fluxes. Since the balance of incoming and outgoing radiation (Figure 2.1) determines Earth's global temperature, these quantities are critical physical components of climate variability and change.

The 28-year-plus time series of total solar irradiance, total ozone, and outgoing longwave radiation allows researchers to address unique aspects of climate change, climate sensitivity, and cloud feedbacks; however, questions remain. Termination of the solar irradiance, energy budget, and ozone profile time series will leave unan-

¹¹The decadal survey missions represent a set of community consensus priorities spanning Earth science including, but not limited to, climate science. Participants were asked to consider whether missions in the decadal survey mission set might enable recovery of NPOESS climate measurements to determine whether there are opportunities for synergism between NPOESS climate measurement recovery strategies and implementation of the community consensus decadal survey plan. Mitigation strategies were considered entirely within the context of climate measurement recovery and are not to be construed as a review of decadal survey mission priorities. The notion of synergy versus competition with the decadal survey is further discussed in Chapter 3, "Cross-Cutting Issues."

¹²See http://www7.nationalacademies.org/ssb/SSB_NPOESS2007_Presentations.html.



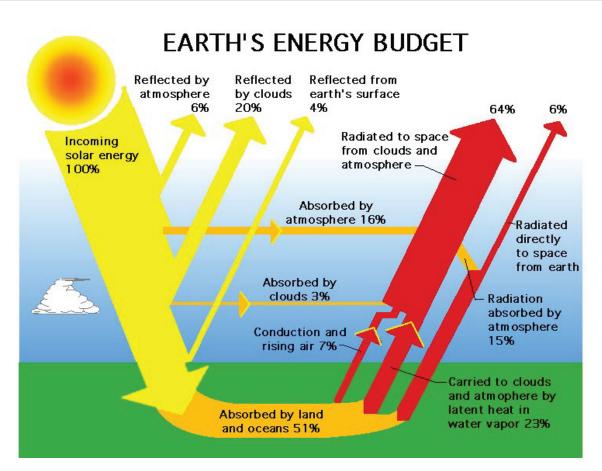


FIGURE 2.1 Diagram of Earth's radiation budget identifying the components that the three demanifested NPOESS sensors were to measure. SOURCE: After NASA Langley Research Center, "The Earth's Energy Budget," CERES S'COOL Project: Clouds and the Earth's Radiant Energy System Students' Cloud Observations On-Line. Available at http://asd-www.larc.nasa.gov/SCOOL/budget.jpg.

swered crucial questions concerning the Sun's impact on climate, both from direct surface heating and indirectly through its modulation of ozone and the stratosphere; the recovery (or not) of the ozone layer from chlorofluorocarbon reductions; the climatic impacts of a changing stratosphere; and the high-precision monitoring of clouds, aerosols, and ocean heat storage over the globe.

Total and Spectral Solar Irradiance

The TSIS instrument that would have flown on NPOESS comprises the Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM) components, copies of which are currently operating successfully on the NASA SORCE (Solar Radiation and Climate Experiment) free-flying spacecraft (launched in 2003).

The SORCE TIM sensor provides improved absolute accuracy and long-term stability relative to the radiometers flown on the Nimbus-7, Solar Maximum Mission, Upper Atmosphere Research Satellite (UARS), ACRIMSAT,

and SOHO spacecraft. ACRIMSAT (launched in 1999) and SOHO (launched in 1995) are still operating. The SORCE SIM instrument is the first to measure the visible and near-infrared spectral irradiances, and it continues the monitoring of the middle UV spectrum, done earlier by UARS.

A TIM instrument is scheduled to fly on the Glory mission (launch in late 2008, 3-year mission design lifetime, 5-year goal), after which there are no current plans to ensure continuation of the 35-year record of total solar irradiance. The end of the SORCE mission in 2011 (assuming a 4-year extension of the core 5-year mission) will terminate a 9-year record of solar visible and infrared spectral irradiance and a 20-year record of solar ultraviolet spectral irradiance. Solar irradiance measurements from 1978 to 2013 will have sampled only three 11-year irradiance cycles, which alone is insufficient time to determine whether long-term irradiance trends occur or to quantify the broad range of irradiance changes possible in activity cycles of varying strength.

Earth Radiation Budget

Earth's radiation budget parameters have, like solar irradiance, been measured since 1978 via instruments onboard seven different spacecraft. Each CERES instrument contains three scanning thermistor bolometer radiometers to monitor the longwave and visible components of Earth's radiative energy budget. CERES achieves high radiometric measurement precision and accuracy, and it measures comprehensive Earth radiation budget parameters at higher accuracy than did its predecessors. CERES instruments on TRMM (launched 1997), Terra (launched 1999), and Aqua (launched 2002) have significantly enhanced capability relative to that of the initial sensors flown on Nimbus 7, ERBS, NOAA-9, and NOAA-10.

The paired CERES on Terra and on Aqua provide both of those missions with the possibility of coincident fixed azimuth plane scanning from one and rotating azimuth plane scanning from the other CERES, enhancing the quality of the final products. The CERES Terra and Aqua biaxial scan mode permits observations of the angular radiation fields in order to greatly improve the accuracy of the final fluxes of solar and thermal energy used to derive Earth's radiation balance. These biaxial observations allow future missions in the same 10:30 or 13:30 orbits to fly a single CERES instrument while achieving the same accuracy as Terra and Aqua. The demanifesting of ERBS, which was to have had the same performance specifications as CERES but updated components, means that Earth radiation budget measurements will terminate with the CERES measurements on Aqua. While the CERES instruments are the most accurate broadband instruments yet flown, they are still not accurate enough to observe the subtle but critical decadal climate change signals unless the instruments are overlapped for at least 6 months in orbit according to the GCOS climate-monitoring principles. ¹³ For this reason it is crucial that measurement record gaps are avoided. Both on-orbit CERES instruments have already exceeded their 5-year mission design life.

Ozone Profile

The total column and the vertical profile of ozone have been measured from space since 1978, primarily by the TOMS and SBUV instruments, respectively. The NPOESS OMPS-Nadir sensor is a combined TOMS/SBUV sensor. Although the SBUV is capable of measuring the ozone profile, its spatial resolution is poor (250 × 250 km), and the observations extend only above the peak ozone concentration. Therefore, the original OMPS design also included a limb sensor (OMPS-Limb) to achieve much higher spatial resolution and, in addition, measure the entire ozone vertical profile, including in the troposphere, below the stratospheric peak. Elimination of OMPS-Limb from NPOESS means that measurements of the complete ozone profile will end upon completion of the Aura mission (launched in 2004 with a 5-year mission design lifetime). The OMPS-Nadir sensor on NPOESS will continue only the total column ozone record.

¹³See http://www.gosic.org/gcos/GCOS-climate-monitoring-principles.htm.

Summary of Breakout Group Discussions

Participants in the breakout discussion considered various mitigation options for each demanifested sensor. A common theme throughout the session was the general preference for free flyers rather than a remanifesting of sensors on NPOESS, although the advantages of assimilation onto an operational platform in terms of data continuity were also noted. Should free flyers play a role in NPOESS mitigation, some participants indicated that there would be requirements for formation flight with the NPOESS platforms that might present a requirement for station keeping for NPOESS itself. The ability of the Integrated Program Office to accommodate such a requirement is uncertain.

TSIS. Although "absolute calibration" has been a goal, expected accuracy has yet to be demonstrated, and so the overlap requirement remains. Ensuring the continuity of the solar irradiance record requires the flight of TSIS indefinitely, overlapping with the current observations. With the demanifesting of TSIS from NPOESS, the sensor can be flown only if provided to the program as government-furnished equipment. In the near term, TIM on Glory will overlap with TIM on SORCE. However, with the earliest flight of a remanifested TSIS on C2 in 2016, the likelihood of a measurement gap is high. Some participants noted that assimilation of total solar irradiance (TSI) and spectral solar irradiance (SSI) observations into the NPOESS operational environment would ensure eventual continuity of the measurements in the longer term, but with an increased risk of gaps in the near term.

The participants considered several mitigation scenarios, which are summarized below.

Mitigation Scenario 1. In scenario 1, the TIM instrument flies on Glory, as planned, in 2009 (continuing the record of total solar irradiance) and NASA builds two additional TSIS (containing TIM and SIM for total and spectrally resolved irradiance measurements) instruments for NPOESS C2 (2016) and C4 (2022). Most participants felt that this option, involving eventual restoration of the TSIS instrument to the NPOESS platform, provided for the eventual continuity of total and spectral irradiance observations in the longer term. However, the potential risk is high for creating gaps in total solar irradiance and SSI records. It was also noted that waiting for an NPOESS C2 launch would very likely create a gap, avoidable only in the (unlikely) event that SORCE continues beyond 2016, a mission life of over 13 years.

Mitigation Scenario 2. Scenario 2 includes all the provisions of scenario 1 but adds TSIS to the LDCM in 2011. This scenario would provide the opportunity to avoid an otherwise-likely data gap, but a solar pointing platform or mechanism would have to be provided to accommodate TSIS. In this scenario, a gap in TSI observations will likely be avoided, provided that there is sufficient overlap of SORCE, Glory, LDCM, and NPOESS C2. The probability of a gap in SSI is also reduced, since SORCE SSI measurements need only continue beyond 2011 (instead of beyond 2016). LDCM is a high-priority mission that reduces the probability of launch delays that could create a gap in the irradiance data.

Mitigation Scenario 3. Scenario 3, which was preferred by most of the breakout session participants, involves flying TSIS on LDCM and then on subsequent free flyers in 2014 and 2020. Having a dedicated mission is considered desirable in order to reduce the higher integration costs presumed for a multisensor Earth-pointed platform and to allow flexibility in planning and launches. During discussions, a participant noted that free flyers can be canceled more easily than can a multiple-sensor mission; he considered this a potential drawback. However, in the short time available for discussion, the potential trade-offs involved in free flyers versus alternatives could not be explored in detail.

Other Mitigation Options. Participants also discussed other options for securing the TSIS data record, including acceleration of the decadal survey recommendation for CLARREO, flying a series of dedicated spacecraft,

and accommodation of TSIS on already-planned missions as an instrument of opportunity (e.g., on GOES-R or DSCOVR). The drawbacks of these options include the risk of relying on unapproved missions, the perceived higher risk of cancellation of single-instrument missions, and physical ¹⁴ and programmatic instrument accommodation challenges, respectively.

ERBS. Ensuring a long-term record of Earth's radiation budget requires the flight of ERBS-type sensors indefinitely, overlapping with Aqua in the near term. CERES is currently manifested on C1 and the NPOESS ERBS was canceled, making an ERB gap likely. To avoid a gap with Aqua, many participants strongly suggested that CERES FM-5 should fly on NPP rather than C1 (2013).

Participants considered several mitigation scenarios, which are summarized below. Some also offered several suggestions for CERES upgrades or improvements, including changes to the mirror attenuated mosaic (MAM)¹⁵ to facilitate solar calibration, switching the 8-12 µm window channel with the ERBE longwave channel to improve determination of longwave and shortwave flux components, and changing materials and instrument operation to avoid UV degradation of the solar channel.

Mitigation Scenario 1. Scenario 1 involves flying CERES on NPP in 2009 rather than on NPOESS C1 to avoid a gap with Aqua, while developing ERBS or a CERES-II for NPOESS C1 and C3. This scenario ensures continuation of ERB measurements on an operational platform and reduces the risk of a gap by a factor of three for putting ERBS on C1 (based on an engineering model of instrument and spacecraft failure rates). A downside of choosing a CERES-II approach is that the original CERES instrument team has been disbanded and the technology is old, so costs, risks, and available capability for building the instruments are unknown.

Mitigation Scenario 2. Mitigation scenario 2 for providing the needed measurement during the NPOESS program span is to fly the existing CERES on NPP and develop ERBS for launch on two subsequent free flyers. Because generation of the Earth radiation budget CDR requires inputs from other sensors on NPOESS, the free flyers would have to fly in formation with the NPOESS 13:30 spacecraft (within 5 minutes of VIIRS coverage). Some participants again noted the advantages of dedicated missions, which allow for flexibility in mission planning and launch dates, but acknowledged the increased risk of cancellation of individual free flyers and of thus jeopardizing measurement continuity.

Other Mitigation Options. Flying ERBS on the decadal survey's recommended CLARREO mission was considered; however, the orbits were found to be incompatible, as the CLARREO mission concept (as it is currently defined) requires precessing orbits, whereas the ERBS continuation of CERES requires a 13:30 Sun-synchronous orbit. The CLARREO and ERBS observations could be directly compared, however, during orbit crossings of CLARREO with NPP and/or the NPOESS 13:30 orbit.

OMPS Limb Subsystem. OMPS-Limb was removed from the NPOESS manifest as part of Nunn-McCurdy certification. Omitting OMPS-Limb will result in the complete loss of precise information about the ozone-height profile after 2014, because OMPS-Limb was the only instrument planned to fly after Aura that would be capable of determining ozone profiles below the peak concentration in the stratosphere.

Some participants noted that even though a descoped OMPS on NPOESS will continue total-column ozone measurements, the OMPS-Nadir sensor lacks the state-of-the-art capability for measuring other trace species

¹⁴Physical accommodation challenges include, for example, instrument sensitivity to the planned mission's radiation and thermal environment, as well as ability to fit within the spacecraft's available payload resource allocations. Programmatic challenges include the perceived cost, schedule, and technical risk associated with accommodating an additional instrument.

¹⁵The mirror attenuated mosaic is a low-scattering mirror used to attenuate and reflect solar radiation into the fields of view for the broadband shortwave (0.2 to 5 μm) and total (0.2 to 50 μm) Earth Radiation Budget Experiment scanning radiometers.

and for high spatial resolution, both of which are essential for advancing atmospheric research in the future. Furthermore, OMPS-Nadir measurements are duplicated by GOME-II on MetOp, which has a smaller footprint (\sim 40 km \times 40 km). The GOME-II instrument also measures aerosols, NO₂, SO₂, BrO, and OClO. With the availability of the higher-resolution OMI data, the science community has realized that OMPS-Nadir and GOME-II have inadequate spatial resolution—thus, there is a desire for higher resolution and more capable sensors than OMPS-Nadir.

For near-term mitigation, most participants would have the 2010-2014 NPP mission fly both OMPS-Nadir and OMPS-Limb, since OMPS-Limb is already built (NASA and NOAA have indicated that OMPS-Limb will indeed be flown on NPP¹⁶).

Mitigation Scenario 1. The most basic mitigation scenario involves remanifesting of OMPS-Limb onto all NPOESS satellites flying OMPS-Nadir. Some participants suggested that because OMPS-Limb and OMPS-Nadir were designed as an integrated package and thus share common electronics, reintegration of OMPS-Limb would present a low risk and should be low in cost. The expected launch date of C3, however, presents a measurement gap risk beyond Aura and NPP.

Mitigation Scenario 2. Scenario 2 involves flight of the OMPS suite (nadir and limb) as above, but replacing the C3 flight with a free flyer. Many participants again noted the advantages of dedicated missions, which allow for flexibility in mission planning and launch dates; however, they also acknowledged the increased risk of cancellation of individual free flyers, which jeopardizes measurement continuity.

Mitigation Scenario 3. Participants discussed a scenario involving flight of solar occultation instruments (e.g., SAGE or Canadian ACE) on free flyers in inclined, precessing orbits to ensure continuity of measurements of stratospheric ozone and pertinent trace-gas profiles. Many participants again noted the advantages and risks associated with free flyers.

Other Mitigation Scenarios. Participants also discussed the relevance of the GACM mission recommended by the Earth science decadal survey. Although it was noted that GACM would provide higher resolution than OMPS, its anticipated launch date is too far in the future for GACM to be relied on as a mitigation option. The flight of an OMI follow-on instrument would preserve the continuity of Aura's higher-resolution ozone data, but only at nadir—meaning that a limb capability would still be needed. GOME-II was also discussed as a possible source of some desired trace gas information, but the spatial resolution is relatively low, and the MetOp 9:30 orbit would present difficulty in merging the data into the current data record.

Visible and Infrared Imager and Sounder Measurements

Background

Nunn-McCurdy NPOESS certification resulted in the demanifesting of APS and reduced the coverage of CrIS/ATMS. The VIIRS sensor has experienced hardware challenges that might impair the sensor's ability to meet certain IORD objectives. A brief background on each of the sensors is presented below. Mitigation options were explored for APS (the demanifested sensor), and participants made suggestions and comments regarding VIIRS and CrIS/ATMS.

VIIRS

Operational 2010+ low-Earth-orbit (LEO) environmental monitoring will be provided by the NPOESS VIIRS. VIIRS combines and dramatically improves upon the POES AVHRR and the DMSP Operational Line Scanner

¹⁶Press Release: NOAA, NASA Restore Climate Sensor to Upcoming NPP Satellite, April 11, 2007, available at http://www.nasa.gov/home/hqnews/2007/apr/HQ_07085_NOAA_NASA_instrument.html.

(OLS). Combining AVHRR and OLS capabilities into a single sensor will provide advantages of simultaneity along with dramatic improvements in spatial resolution and radiometry for vegetation index, SST, cloud top temperature, and day-night cross-terminator cloud imaging for DOD applications.

Moreover, to satisfy the VIIRS EDRs prescribed by the NPOESS IORD, VIIRS will also provide many of the scientific remote-sensing features of the Earth Observing System (EOS) MODIS and SeaWiFS instruments. VIIRS offers most MODIS and SeaWiFS capabilities except near-IR and microwave/IR water vapor bands, IR sounding bands, and near-IR fluorescence radiometry not required to meet the prescribed VIIRS EDRs. VIIRS will also dramatically improve on MODIS and SeaWiFS spatial resolution (via a patented OLS-like¹⁷ detector aggregation technique) and global coverage (via a 40 percent wider imaging swath), while offering comparable absolute radiometry and sensitivity as well as the long-term stability required by the IORD to support CDRs. Indeed, most of the 23 VIIRS EDRs are also ECVs.

VIIRS is manifested on the NPP and is planned for a 13:30 Sun-synchronous orbit as part of the EOS "A-Train," to augment the EOS Aqua spacecraft carrying MODIS, and to complement the NOAA N' and DMSP midafternoon spacecraft. Following NPP, the NPOESS C1 spacecraft carrying a VIIRS will operate in the terminator orbit to replace the DMSP F16. Finally, the NPP will be replaced by NPOESS C3; the operational replacement for the DMSP, NOAA N', and EOS Aqua satellites, all operating in midafternoon orbits.

The pre-Nunn-McCurdy NPOESS constellation was also to include NPOESS C2 for the midmorning orbit with a VIIRS to replace the EOS Terra MODIS as well as the NOAA N' and DMSP midmorning AVHRR and OLS, respectively. Post-Nunn-McCurdy, the midmorning orbit has been deleted, and the ESA/EUMETSAT's MetOp-A, which became operational in late 2006, substitutes AVHRR for the NPOESS midmorning VIIRS, offering no replacement for the midmorning OLS or MODIS.

Along with the MetOp AVHRR in the 21:30 orbit (9:30 pm local ascending node—"midmorning" refers to the 9:30 am local descending node), the NPP/MetOp pair will provide continuity of civil environmental imaging, but the deletion of the NPOESS 2130 orbit results in reduced capability, given that the AVHRR on MetOp will only address (and not meet) a fraction of the VIIRS EDRs. In particular, the requirements for VIIRS EDR long-term stability were specified to assist CDR production. The AVHRR is not specified to meet these requirements even for the limited set of VIIRS EDRs it does address.

APS

Aerosol information available from current operational and research satellite observations is primarily in the form of aerosol optical depth, with additional coarse information about particle size provided in the form of a coarse/fine mode discrimination of optical depth or in the form of an aerosol index. Much of this information is restricted to over-ocean observations, given the complexity that land surface adds due to variable surface reflections. The information currently available is far short of what is needed—quantified aerosol absorption is needed to apportion the aerosol forcing contributions between atmosphere and surface—to monitor aerosol forcings of climate. APS offers limited ability for determining the absorbing properties of aerosols, which is nevertheless a significant step forward from existing capabilities.

APS on Glory is scheduled for launch in 2008 and is expected to operate into 2013. With the removal of the APS instrument from NPOESS, VIIRS will by necessity become the principal sensor for deriving aerosol parameters needed for estimation of aerosol climate forcing post-2013. Without a remanifesting of the APS, the monitoring of aerosol forcing beyond 2013 will likely decline to pre-2013 capability, particularly given the uncertain performance of VIIRS.

¹⁷The DMSP OLS is an oscillating scan radiometer designed for cloud imaging. A notable feature of the OLS is its equal resolution across the scan.

¹⁸NRC, Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties, The National Academies Press, Washington, D.C., 2005.

CrIS/ATMS

The power of hyperspectral sounding has been amply demonstrated by the NASA EOS Atmospheric Infrared Sounder (AIRS) flying on the Aqua mission in a 13:30 orbit¹⁹ in terms of improved retrieval uncertainty and a significant positive impact on forecast skill.²⁰ Operational LEO atmospheric temperature and moisture sounding capability in the 2010+ time frame will be provided by two instrument pairs (three during the transition from the current system). The NPOESS program will fly an operational hyperspectral infrared sounder—the Cross-track Infrared Sounder (CrIS). The CrIS instrument will be accompanied by the Advanced Technology Microwave Sounder (ATMS).

The CrIS and ATMS instrument pair is currently manifested on the NPP flight, which is planned for a 13:30 Sun-synchronous orbit as a part of the EOS "A-Train." The NPP will subsequently be replaced with the NPOESS flights C1 and C3; these are the operational replacements for NOAA N'. The NOAA M (midmorning), N, and N' spacecraft carry the current-generation multispectral HIRS, along with the AMSU. In the midmorning orbit, the multispectral sounding capability of NOAA-M is being replaced by the Infrared Atmospheric Sounding Interferometer (IASI) carried on ESA/EUMETSAT's MetOp-A, which became operational in late 2006. The MetOp series carries additional profiling capability via the Microwave Humidity Sounder, Advanced Microwave Sounding Units (AMSU-A1 and AMSU-A2), and High-resolution Infrared Radiation Sounder (HIRS/4).

Retrieved variables from CrIS and ATMS include temperature, moisture, and pressure profiles, surface emissivity and temperature, total-column ozone, and additional possible data products such as trace gases (CO, N_2O , CH_4 , and CO_2). In particular, upper-air temperature and water vapor are considered to be global ECVs.

The demanifesting of CrIS/ATMS from the NPOESS 17:30 orbit results in reduced coverage, because the CrIS/ATMS ±48.3° cross-track scans and 2,250 km swaths do not provide global contiguous coverage. The reduction from three to two orbit planes for atmospheric moisture and temperature profiling represents a loss in diurnal sampling (from 4- to 6-hour refresh) compared to the pre-Nunn-McCurdy NPOESS baseline, which will reduce the quality of diurnally averaged climate analyses. It should be noted, however, that the current operational satellite architecture of NOAA POES, DMSP, and MetOp does not include a 17:30 infrared sounder, and so coverage will not worsen, but rather fail to improve over that provided by the current system. This reduction in diurnal coverage is compounded by the recent NOAA decision to suspend taking operational geosynchronous upper-air temperature and water vapor profile measurements after the current GOES-N/O/P series until approximately 2025.

Summary of Breakout Group Discussions

A number of mitigation options and instrument improvements were considered for APS, VIIRS, and CrIS/ATMS. An idea that received particular attention was that on all subsequent flight builds there would be extensive preflight characterization and improved documentation to increase climate science utility (to date this is not currently planned); these preflight characterizations would ensure that the sensors are stable, as nearly identical as possible from sensor to sensor, and thus climate relevant.

Two of the mitigation options discussed below were identified by some participants as involving small to moderate changes to existing instruments that might be accomplished with minimal additional investment and could yield high returns to the climate science community. Specifically:

- The VIIRS fire product (the VIIRS active fire EDR) can be improved by adding an M15 saturation flag. Participants familiar with the instrument design suggested that this might be possible to implement early in the program (as soon as NPP).
 - CrIS/ATMS data can be downlinked at full spectral resolution to enable production of additional climate

¹⁹The Aqua orbit is controlled to maintain an ascending node equatorial crossing time of 13:30 local time.

²⁰J. Le Marshall, "The Use of Global AIRS Hyperspectral Observations in Numerical Weather Prediction," 11th Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface, 87th American Meteorological Society Annual Meeting, San Antonio, Texas, January 15-18, 2007, available at http://ams.confex.com/ams/pdfpapers/119660.pdf.

data products without changes to the hardware. Increased preflight testing and documentation would also be necessary to produce climate-quality greenhouse gas measurements from the instruments.

VIIRS. A comparison of MODIS and VIIRS was presented. It was noted that the MODIS functional architecture is a flat "paddle" scan-mirror favored for midmorning and afternoon orbits while the VIIRS functional architecture is a rotating telescope required for terminator orbits. VIIRS will provide improved imagery (with more constant field of view than MODIS), but VIIRS has no IR channels sensitive to atmospheric H₂O (or CO₂). Regarding EDR performance, VIIRS is expected to meet all requirements, and in tandem with CrIS improves on most.²¹

VIIRS is currently progressing through vacuum tests. While emphasizing the importance of not disrupting these tests so as to maintain schedule, several participants noted a number of highly desirable improvements. In particular, the VIIRS fire product can be improved by mitigating the aggregation of saturated pixels with nonsaturated pixels, or at least providing a flag. In the future, a higher saturation level in the shortwave infrared window should be considered; this could be accomplished with a dual-gain sensor and likely not affect SST determinations. The inclusion of water-vapor-sensitive measurements that enable estimation of winds over the poles day and night is planned for the C3 VIIRS and should be pursued. It was noted that synergy with the visible/near-infrared (NIR) channels on ABI has been suggested and is planned; this synergy provides in-flight calibration opportunities for the geostationary ABI sensor (which lacks on-board visible/NIR calibration) leveraged from the LEO sensor (VIIRS with onboard calibration).

Finally, to achieve comparable imaging capabilities in the midmorning orbit, participants advised that the Integrated Program Office work with EUMETSAT to fly a VIIRS imager on subsequent MetOp platforms so that an imager more capable than the AVHRR is flying in the midmorning (MetOp) orbit as soon as possible.

One participant noted that MODIS displays problems with saturation that could be mitigated for VIIRS by incorporating dual gains especially for the 746 nm channel, and further suggested that signal-to-noise improvements by a factor of two in the 1,240 and 1,610 nm bands would enhance the ocean-sensing capabilities of VIIRS significantly. This participant noted that VIIRS could be very helpful to the ocean CDR (even more so with the above-mentioned improvements).

APS. The APS instrument scientist for Glory, Brian Cairns, delivered a presentation regarding APS and APS-MODIS/VIIRS synergy. Dr. Cairns noted that aerosols come in various sizes and shapes; the key requirement is to determine the type of aerosol that is present. APS is intended to assist in measuring particle composition and size and shape. There are two cloud data products and an experimental product that are thought to be able to infer cloud base height. Instantaneous field of view cloud screening of APS at 6 km is accomplished using VIIRS/MODIS. Summarizing the APS and MODIS/VIIRS synergy, Cairns remarked, "APS with MODIS/VIIRS tells you a lot, but alone APS tells you nothing."

Mitigation options considered by the participants are summarized below.

Mitigation Scenario 1. In scenario 1, APS will fly on Glory as a demonstration, and if successful will be integrated onto NPOESS C3. Many participants believed APS on Glory would begin a valuable record; however, it was also noted that NPOESS C3 does not have a needed lunar calibration capability.

Mitigation Scenario 2. Scenario 2 includes the elements of scenario 1 but adds a climate free flyer between Glory and C3. The added value of this scenario is the continuation of the aerosol data record, with the ability to lunar-calibrate APS on the free flyer. A variation on this option considers another free flyer in place of reintegration onto C3. This approach would avoid the concern about lack of lunar calibration associated with C3, although likely at a higher cost.

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²¹For more detail, see C.F. Schueler and W.I. Barnes, "Next-Generation MODIS for Polar Operational Environmental Satellites," *Journal of Atmospheric and Oceanic Technology* 15(2):430-439, 1998.

Mitigation Scenario 3. Another scenario involves proceeding with the ACE mission recommended in the Earth science decadal survey. This mission calls for cross-track polarimetric coverage, which is an advance over the single-pixel APS; however, the technology readiness of such an instrument was questioned by some participants. The perceived low technology readiness level²² of the polarimeter was also considered a risk of this scenario.

CrIS/ATMS. The role of AIRS/IASI/CrIS-ATMS in climate research was discussed. It was noted that the requirements for AIRS and CrIS are similar and that hyperspectral infrared measurements have been demonstrated to improve weather forecasting, largely accounting for the initial decision to include CrIS on NPOESS. AIRS has demonstrated a positive impact in weather forecasting, but the hyperspectral IR also helps in climate observations. AIRS radiances are accurate and traceable to National Institute of Standards and Technology (NIST) standards. Further, AIRS is stable as verified by ground truth. With cross-calibrations, hyperspectral IR measurements have been used for quality control for other sensors (including MODIS). Some participants stated that the advent of spectrally resolved NIST-traceable infrared measurements will assist climate science appreciably.

In subsequent discussion, breakout participants considered having CrIS/ATMS restored to the early morning orbit so that the diurnal cycle would be measured adequately. A breakout participant suggested that data with the full spectral resolution measured by CrIS be downlinked so that more accurate trace gas measurements could become available. Some participants also discussed their desire for additional improvements to hyperspectral sounding capability, including a dedicated sounder free flyer.

Microwave Sensor Measurements

Background

The NPOESS altimeter, ALT, was demanifested as a result of the Nunn-McCurdy action, and CMIS is being restructured as a (still largely undefined) MIS instrument with reduced capability. In light of these changes, the microwave sensor breakout session divided its presentations and discussion into three subsessions: altimetry, radiometry, and scatterometry. While scatterometry was not considered as part of the NPOESS baseline, some participants felt that the pressing need for continuation of operational active ocean vector wind measurements warranted further discussion, particularly in light of the CMIS descope. Further, some participants asserted that passive microwave vector wind measurements did not constitute a climate data product, whereas the value for climate studies of scatterometry-derived wind measurements has been demonstrated.

ALT/Altimetry

A 15-year CDR of global sea level rise and interannual variability has been established by TOPEX/Poseidon (1992-2002) and Jason (2002-present).²³ The duration of this data record is just beginning to provide insight into decadal variability. Altimeter data are used extensively in observationally based studies of ocean climate variability on seasonal and longer time scales. These data are also assimilated into many ocean circulation models. The 15-year sea level data record has established a unique record of the effects of global warming. As the ocean absorbs more than 80 percent of the heat from global warming, the information on the state of ocean circulation revealed from altimetry is also important for understanding climate change. The altimetry sea level record is crucial for checking the validity of the assessment of the extent of global warming and future projections and for monitoring the effects of global warming. The continuation of a precise sea level record is thus of unique and critical importance.

²²Technology readiness levels are defined in J.C. Mankins, "Technology Readiness Levels: A White Paper," NASA Advanced Concepts Office, April 6, 1995, available at http://www.hq.nasa.gov/office/codeq/trl/trl.pdf.

²³The rate of sea level rise has been approximately 3.5 mm/year. See E.W. Leuliette, R.S. Nerem, and G.T. Mitchum, "Results of TOPEX/ Poseidon and Jason-1 calibration to construct a continuous record of mean sea level," *Marine Geodesy* 27:79-94, 2004, and B.D. Beckley, F.G. Lemoine, S.B. Luthcke, R.D. Ray, and N.P. Zelensky, "A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits," *Geophysical Research Letters* 34(14):L14608, 2007.

There are a number of other altimetry missions planned for the next decade: the France/India AltiKa/SARAL mission, the ESA Sentinel-3 mission, and the Chinese HY-2 mission. These missions will certainly complement precision altimetry missions but cannot be relied on as alternate approaches to the continuation of the sea level record because of their non-optimal orbits for resolving ocean tides, less accurate orbit determination, and the lack of an associated well-balanced science program focused on sea level and ocean circulation.

Although the present record will be continued by the follow-on mission to Jason—the OSTM/Jason-2 to be launched in 2008 as a joint mission of NASA, NOAA, Centre National d'Etudes Spatiales (CNES), and EUMETSAT—the next mission after OSTM/Jason-2 is not yet confirmed. The certified NPOESS program does not include an altimeter.

CMIS/MIS/Radiometry

CMIS represented the state of the art in satellite microwave radiometers and was intended to continue, with a higher degree of accuracy and resolution, the time series of many fundamental climate variables, including SST and wind, sea ice and snow coverage, soil moisture, and atmospheric moisture (vapor, clouds, and rain). The ability of CMIS to measure surface characteristics through cloud cover made it a unique and essential sensor for climate.

CMIS had a number of advanced capabilities that are not available from the current operational microwave imaging radiometers SSM/I and SSMIS. These included:

- 1. Low-frequency channels at 6.9 and 10.7 GHz,
- 2. Higher spatial resolution (a factor of three better than SSM/I and SSMIS), and
- 3. Better spatial/temporal coverage: three orbit times as compared to two.

CMIS also had polarimetric channels capable of inferring wind direction, which is addressed elsewhere (see "Scatterometry" below).

The capabilities of the MIS instrument that is to replace CMIS are still largely undefined; however, there were indications that certain low-frequency channels were likely to be lost. The loss of the low-frequency channels, particularly at 6.9 GHz, would mainly impact the measurement of SST and soil moisture, although it also would degrade the accuracy of some other retrievals such as measurements of wind speed. Loss of high spatial resolution would have a detrimental effect on measurements of all parameters, including sea ice, snow cover, and precipitation. Reduced spatial/temporal coverage, due to the deletion of MIS from the midmorning orbit, will significantly limit the ability to characterize the climate's diurnal cycle, especially with respect to global precipitation. The impact on climate monitoring and research of losing these advanced capabilities is substantial.

Microwave "through-cloud" SST measurements have proven to be a boon for climate research and oceanography. Unlike IR measurements, which are limited to cloud-free areas, microwave retrievals provide a largely
uninterrupted view of the surface temperature over the world's oceans. The importance of SST to climate research
is hard to overstate. SST is a key parameter in determining how the water and energy fluxes at the air-sea interface
affect the hydrologic cycle and the surface radiation balance. The intensity, frequency, and location of hurricanes
are in part determined by where the necessary oceanic heat is available to sustain, encourage, or dissipate these
storms. Climate oscillations such as the El Niño Southern Oscillation, North Atlantic Oscillation, and Pacific Decadal
Oscillation all have distinctive SST signatures that characterize the relevant forcings. The endemic cloud cover at
high latitudes prevents monitoring of ocean temperatures by IR radiometers, and microwave radiometers provide
the only way to continually measure SST in these vital Arctic regions, which are now experiencing rapid climate
change. Tropical convergence zones are also prime examples of persistently cloudy regions where SST detection
by AVHRR is problematic. Microwave measurements in the 5-7 GHz band are required to retrieve SST over the
full range of global temperature (–3°C to 35°C).

Soil moisture is a key determinant of the interaction between the land and the atmosphere. In many respects, it plays a role similar to that of SST in the case of air-sea interactions. Soil moisture controls the relationship between actual and potential evapotranspiration and hence is a key determinant of the recycling of moisture from the land surface to the atmosphere. Notwithstanding that 6.9 GHz is limited to sensing soil moisture in the top few centimeters of the soil only in areas of sparse vegetation, the portion of the globe so covered is substantial. Furthermore, the areas where construction of a CDR would be feasible include substantial areas (e.g., of the African continent) where hydrologic extremes have great consequences both economically and in terms of loss of human life. Given the potential for acceleration of the hydrologic cycle associated with global warming, construction of a long-term CDR for soil moisture would have significant scientific and societal value. Furthermore, planned soil moisture missions (ESA/SMOS, NASA/SMAP) at the L-band, while emphasizing a product technically superior to the product that could be derived from a 6.9 GHz channel, are experimental in nature and are not alone intended to produce long-term, multidecadal CDRs. These planned L-band missions would, however, have great value in terms of refining and characterizing the temporal and spatial variability of the 6.9 GHz retrievals.

Sea ice plays a key role in global climate change by regulating ocean-atmosphere transfers of energy and water and helping to control ocean surface salinity. Sea ice albedo feedbacks amplify climate impacts in the polar regions. Variables such as ice extent, concentration, and type are important for navigation as well as for marine habitat assessment. The passive microwave satellite record of sea ice concentration and extent extends from 1979 to the present. Documented decreases of Arctic sea ice extent currently exceed 8 percent per decade and appear to be accelerating. Snow cover in the Northern Hemisphere has also been declining at a rate of about 3 to 5 percent per decade during spring and summer. This decline in snow cover is significant because, compared with other land cover types, snow has a very high albedo and climate feedbacks are felt on local, regional, and even hemispheric scales. Moreover, snowmelt runoff is a key component in the hydrologic cycle and the primary source of fresh water for many millions of people. At a time when Arctic sea ice and snow cover are changing most rapidly, the loss of the all-weather monitoring capability of CMIS represents a major setback.

Global measurements of precipitation will be adversely affected by all three lost capabilities. Accurate measurements of heavy rain require the 11 GHz channels. Higher spatial resolution is essential to discriminate convective versus stratoform features and to measure the intense rain that often comes from small rain cells. Finally, better spatial/temporal coverage is a main prerequisite for improving current knowledge of global rainfall over the complete diurnal cycle. The advanced capabilities of CMIS will be dearly missed by the precipitation community.

The cancellation of CMIS leaves JAXA's AMSR-E and the U.S. Navy's WindSat as the only low-frequency, high-spatial-resolution microwave radiometers in space.

Scatterometry

Data derived from ocean scatterometers is vital to scientists in their studies of air-sea interaction and ocean circulation, and their effects on weather patterns and global climate. These data are also useful in the study of unusual weather phenomena such as El Niño, the long-term effects of deforestation on our rain forests, and changes in the sea-ice masses around the polar regions. These all play a central role in regulating global climate. An 8-year CDR of ocean surface vector winds has been established by QuikSCAT (1999-present). This data set has been crucial in advancing scientific research into marine meteorology, wind-driven upper-ocean circulation, and air-sea interaction processes from local to basin-wide scales. The QuikSCAT measurements have revealed energetic small-scale structure in the surface wind field that was not previously known to exist. The Ekman upwelling from the wind stress curl associated with these structures plays an important role in ocean circulation theory, as well as in ocean biology from upwelling of nutrients from the deep water into the upper ocean where they can be utilized

by phytoplankton. The QuikSCAT data record is approaching the 10-year duration that is considered the baseline minimum for use in numerical simulations of wind-forced ocean circulation.

QuikSCAT is also heavily used in operational severe weather forecasting. The QuikSCAT measurements have had a major impact on tropical cyclone forecasting, especially for cyclones outside the range of aircraft reconnaissance. QuikSCAT data have helped in the estimation of the intensity of tropical storms, in determining the radial extent of winds of tropical storm force in tropical storms and hurricanes, and in locating circulation centers for tropical depressions and tropical storms. QuikSCAT occasionally provides earlier detection of surface circulations in developing tropical cyclones, and some studies have indicated a positive impact on hurricane track forecasts by numerical models, especially over the open-ocean regions that are not accessible by aircraft.

The high resolution of QuikSCAT measurements has improved forecasting, warnings of localized wind events, and ability to locate frontal systems over the ocean. In midlatitudes, QuikSCAT revolutionized wind warning categories by enabling the introduction of hurricane-force wind warnings in 2000. Hurricane-force winds were rarely forecast outside the tropics prior to the availability of QuikSCAT data. During the months of September 2006 through May 2007, forecasters at the NOAA Ocean Prediction Center used QuikSCAT wind measurements to identify 114 individual extratropical cyclones (64 in the North Atlantic and 50 in the North Pacific) containing extreme hurricane-force wind conditions.

In the original configuration of NPOESS, the ocean surface vector wind data record established by QuikSCAT was to be replaced by passive microwave measurements of wind speed and direction by the polarimetric CMIS radiometer. From the beginning, there were serious concerns within the scientific community (both research and operational) about the viability of passive microwave measurements of ocean surface vector winds, especially in storms and in other areas of rain and large amounts of cloud liquid water.

In preparation for CMIS, the U.S. Navy launched WindSat in January 2003 as a "risk reduction demonstration project." WindSat is similar but not identical to CMIS, allowing insight into the accuracy of vector wind retrievals that could be expected from CMIS. WindSat results thus far have not allayed scientists' concerns about passive microwave measurement of ocean vector winds.²⁵

Summary of Breakout Group Discussions

ALT/Altimetry. Workshop participants considered currently operating and planned altimetry missions and their adequacy to meet climate measurement needs. Since the Sun-synchronous orbit of the NPOESS platforms is not acceptable for measuring global sea level change with the required precision, the loss of the NPOESS altimeter has little impact on continuation of this CDR.

The Jason altimeter is expected to continue operating at least long enough to overlap its successor, Jason-2 (also known as OSTM), which is expected to launch in June 2008. Jason-2 is essentially equivalent to the currently operating Jason altimeter. The overlap of TOPEX/Poseidon and Jason enabled the identification of a 14 cm bias between the two altimeters. It is likely that a similar bias will exist between Jason and Jason-2; therefore, an overlap of Jason and Jason-2 is highly desirable in order to cross-calibrate the two altimeters and ensure accurate continuation of the sea level CDR. If there is no overlap, tide gauge data will provide a viable alternative to cross-calibration, as long as the gap between Jason and Jason-2 is not long. While Jason-2 may continue to operate for more than its nominal 5-year lifetime, it is critical that a successor to Jason-2 be launched by 2013 to ensure continuation of a sea level CDR that is indispensable for monitoring the state of the global ocean and its role in future climate variability.

Because of its Sun-synchronous orbit, the currently operating ENVISAT altimeter and its successor Sentinel-3 are not viable mitigation strategies for continuation of the sea level CDR beyond Jason-2. Three mitigation scenarios were discussed. All three consist of a sequence of two successors to Jason-2, referred to here as Jason-3 and Jason-4.

²⁴Windsat is a joint IPO/DOD/NASA risk reduction demonstration project intended to measure ocean surface wind speed and wind direction from space using a polarimetric radiometer. It was launched in January 2006. See http://www.ipo.NOAA.gov/Projects/Windsat.html.

²⁵See, for example, M. Brennan, R. Knabb, P. Chang, J. Sienkiewicz, Z. Jelenak, and K. Schrab, "The Operational Impact of and Future Requirements for Satellite Ocean Surface Vector Winds in Tropical Cyclone Analysis," 61st Interdepartmental Hurricane Conference, March 6, 2007, available at http://www.ofcm.gov/ihc07/Presentations/s4-04brennan.ppt.

Mitigation Scenario 1. In the first scenario, which was the scenario most preferred by participants, Jason-3 consists of a Jason-2-type altimeter to be launched by NOAA and EUMETSAT, and Jason-4 consists of a wide-swath altimeter, referred to in the Earth science decadal survey as the SWOT mission, to be developed and launched by NASA and CNES. To allow for precise intercalibration, the preferred orbit for Jason-3 is the same as that of TOPEX/Poseidon, Jason, and Jason-2. The orbit for SWOT would have to be changed to a higher inclination and longer repeat period in order to satisfy the sampling requirements for the terrestrial water (lakes and rivers) applications. In addition to broadening applications to include measurements of terrestrial water, the synthetic aperture radar-interferometric technology of SWOT will provide much higher resolution measurements for studies of ocean eddies and measurements very near land for coastal applications.

An advantage of this scenario is that Jason-3 would be a clone of Jason-2, in terms of both hardware and being a jointly funded project with EUMETSAT and other European partners. Many components have already been manufactured as spares for Jason-2, including a spare Proteus bus. If partnerships could be secured, the United States would only be responsible for approximately half of the cost of the mission. A potential disadvantage of this two-mission scenario is that the launch of Jason-3 could jeopardize a subsequent launch of the decadal survey's recommended SWOT mission if sufficient funding is not provided for both missions sequentially.

Intercalibration issues between Jason-3 and a SWOT altimeter for Jason-4 would be unavoidable because of the need to change to a different orbit for SWOT. An overlap between Jason-3 and Jason-4/SWOT is therefore highly desirable, although the tide gauge network could also be a viable method for intercalibration. The 10-day repeat orbit for Jason-3 in this scenario would not satisfy Navy requirements. SWOT's higher-inclination orbit provides a wider swath and a repeat period that would satisfy Navy requirements.

Mitigation Scenario 2. In the second scenario, Jason-3 and Jason-4 are both Jason-2-type altimeters in the same orbit that has been used for TOPEX/Poseidon and Jason, which is also to be used for Jason-2. This scenario would eliminate any issues with cross-calibration and would thus ensure continuation of the CDR for sea level rise. The primary disadvantage of this scenario is the delay in the launch of a SWOT altimeter, thus postponing the capabilities to measure the full spectrum of eddy variability in the ocean, to measure sea surface height near land, and to measure terrestrial water. Another issue for this scenario is that there are no spare satellite buses available for Jason-4.

Mitigation Scenario 3. Jason-3 is a SWOT-type altimeter. The advantage of scenario 3 is the near-term broadening of applications of satellite altimetry to include studies of ocean eddies, near-coastal sea level variability, and terrestrial water. A potential disadvantage is the possibility of a gap occurring in the sea level CDR due to limitations in how quickly SWOT could be built, tested, and launched. Since the orbit of SWOT would be different from that of TOPEX/Poseidon, Jason, and Jason-2, potential problems with cross-calibration for continuity of the sea level CDR would be an issue. An overlap between Jason-2 and Jason-3/SWOT is therefore highly desirable, although tide gauge data could also be a viable method for intercalibration.

CMIS/MIS/Radiometry. Participants in the radiometry breakout session focused on the likely loss of capability of the CMIS instrument, which was canceled and is to be re-competed as a simpler, less capable instrument launching no earlier than 2016 on NPOESS C2. This descope and delay were of most concern for applications requiring the 6.9 GHz band, which is of prime importance for measurement of global SST and soil moisture. As noted earlier, many participants were less concerned about the potential loss of ocean vector winds measurements from CMIS, because this CMIS data product was considered inadequate even prior to the descoping; ocean vector wind measurement is addressed further in the section "Scatterometry" below.

Two presentations were given on the importance of microwave SST retrievals to climate studies. One talk stressed the strong synergism that is obtained when microwave SST retrievals are combined with IR SST retrievals; both are necessary for doing climate research. The other presentation focused on the detrimental impact associated with the cancellation of CMIS and then suggested several possible mitigation strategies. Global SST retrievals require a channel near 6.9 GHz, and currently only AMSR-E and WindSat have this low-frequency channel.

CMIS also had a 6.9 GHz channel, but with its cancellation there is a very high risk that a break will occur in the microwave SST climate record when AMSR-E and WindSat cease to operate. Both sensors are past their mission design lifetimes, and AMSR-E is experiencing some torque anomalies. The soil moisture CDR, which also requires the 6.9 GHz channels, will suffer a break as well.

Without any mitigation measures, the future for low-frequency, high-resolution microwave radiometry looks austere. A follow-on AMSR-2 is scheduled to fly on JAXA's GCOM-W platform, but not until 2012, and no follow-on is planned for WindSat. NASA's GMI radiometer is scheduled for launch in 2013, but it does not have the 6.9 GHz channels or the high spatial resolution of CMIS and AMSR. In addition, GMI will not view the high latitudes due to its low-inclination orbit. In 2016, assuming no more delays, NPOESS will launch MIS, a descoped version of CMIS with capabilities yet to be defined. One participant noted that this "thin thread of current and future microwave missions is completely inadequate for climate monitoring and research." It was pointed out that a significant launch delay of MIS past 2016 could be disastrous. The DMSP F-series of satellites comes to an end at the end of the next decade. The microwave imagers SSM/I and SSMIS on these DMSP satellites have provided the research community with extremely important CDRs, including sea ice coverage, water vapor, wind speed, rainfall, and cloud water. A break in any of these time series due to a delay or aborted launch of MIS would be devastating to climate monitoring.

With respect to descoping CMIS to MIS, there was strong support for maintaining the low-frequency channels, particularly 6.9 GHz, and also for maintaining the high spatial resolution of AMSR-E and WindSat. Most participants considered these capabilities more important than maintaining the polarimetric channels for wind direction retrievals; the preferred approach for obtaining wind direction was via scatterometry.

Several mitigation strategies were discussed.

Mitigation Scenario 1. The first scenario involves making the most of what is possible now with AMSR-2 and MIS by advising NASA and NOAA to establish a memorandum of understanding with JAXA that would make the AMSR-2 data and the supporting documentation that is required to develop CDRs freely available to the research community. The workshop discussion stressed the need for proper documentation for each satellite data stream to be freely available to the user community as an aid to application of the data within the CDR. In addition, science teams need to be funded to utilize the AMSR-2 data for climate research. However, there were some concerns expressed about relying too much on AMSR-2 because of past problems with platform stability and longevity, and some additional mitigation was thought to be highly desirable.

Mitigation Scenario 2. The second mitigation scenario is to add a 6.9 GHz channel to GMI. Currently the lowest channel on GMI is 11 GHz, and it is feasible that a 6.9 GHz channel could share the same feedhorn as the 11 GHz channel. It is also possible that the size of the GMI antenna could be increased. However, the GMI project has already undergone several delays, and it is not clear if these new modifications would be possible considering the current schedule. Another drawback is that SST in polar areas will not be observed by GMI.

Mitigation Scenario 3. The third mitigation scenario, most intriguing to many participants, is to enhance the microwave radiometer onboard the planned (but not yet funded) XOVWM, which has a suggested launch date around 2012. The synergy of an active scatterometer and a passive radiometer on the same platform is significant and would improve both the scatterometer vector wind retrievals and the radiometer SST retrievals. As currently planned the XOVWM radiometer has channels at 6.9 and 14 GHz. It also has a very large antenna that will provide higher spatial resolution than would AMSR-E. To obtain accurate SST retrievals, at least one higher-frequency channel would be required and the onboard calibration system would have to be improved. The feasibility of these enhancements needs to be investigated.

Mitigation Scenario 4. A final mitigation strategy is a free-flyer radiometer with AMSR-type capabilities. Existing radiometers such as GMI (with a 6.9 GHz channel), JAXA AMSR-2, or WindSat are all possibilities. However, this would be a costly scenario in that it would require an entirely new mission.

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Other Breakout Group Discussions. In addition to mitigation strategies, a few other matters were discussed, including the idea of reinstating microwave sounding channels on the morning NPOESS platform. For this purpose, ATMS is preferable to sounding channels on MIS. Interest in this approach comes from the need to continue the MSU/AMSU tropospheric and stratospheric temperature CDRs without any spurious discontinuities. These temperature time series have been based on a combination of morning and afternoon orbits for the last 28 years and represent one of the most important CDRs coming from satellite remote sensing.

Scatterometry. Breakout group participants discussed the CDR that exists thus far for ocean vector winds, based primarily on 8 years of QuikSCAT measurements. Other platforms' contributions were discussed, including those of ASCAT and WindSat. These discussions are briefly described here, although the discussion was extensive.

Some participants noted that the currently operating ASCAT scatterometer on MetOp will not maintain the CDR established by QuikSCAT, primarily because of sampling inadequacy; the combined coverage of the two parallel measurement swaths of ASCAT is only approximately 55 percent that of QuikSCAT. The 720 km gap between the two ASCAT swaths exacerbates these sampling problems. In addition, the spatial resolution of ASCAT is half that of QuikSCAT, which limits ASCAT's usefulness in coastal applications to those that are about 50 km or farther from land, and in the resolution of small-scale features in the wind field such as hurricane structure, fronts, and jets. ASCAT also has a different wind directional ambiguity structure that results in larger potential errors in the interpretation of vector wind fields. Further, because of the reduced sensitivity of vertically polarized radar returns to high winds compared with horizontal polarization and the fact that ASCAT is a single-channel vertically polarized radar, the performance of ASCAT in high-wind conditions remains to be demonstrated.

Some participants also remarked on the difficulty of assessing the accuracy of WindSat estimates of wind speed and direction due to frequent updates of the wind retrieval algorithms under development by the Navy, although the evolving nature of these algorithms was not considered surprising in view of the newness of the passive microwave technology for measurements of ocean surface vector winds. In presentations to the participants, WindSat wind retrievals (based on 4 years of data) were compared with QuikSCAT observations. Based on analyses of these comparisons, the following observations were made:

- There is significantly larger wind direction uncertainty in WindSat retrievals at low-to-moderate wind speeds;
- Depending on the version of the algorithm, WindSat wind retrievals can be biased either high or low in high-wind-speed conditions such as hurricanes and extratropical cyclones;
- WindSat retrievals of wind vectors are more susceptible to error in cloudy and rainy conditions, which are
 often associated with extreme weather events; this susceptibility may affect the use of WindSat data in forecast
 systems and for wind warnings and the development of accurate climatologies of such events;
 - The spatial resolution of WindSat is less than half that of QuikSCAT;
- The coverage of the WindSat measurement swath is only approximately 55 percent that of QuikSCAT;
 and
- Passive measurements are much more subject to contamination by land in the antenna sidelobes; as a result, WindSat's retrievals are not possible within approximately 75 km of land.

While some of these issues are being addressed by ongoing improvements in the WindSat retrieval algorithms, several participants expressed the strongly held view that passive microwave measurements would never be comparable in accuracy, coverage, or resolution to the measurements from a radar scatterometer. Passive microwave measurements would be especially problematic in cloudy and rainy conditions and for measurement of winds near land.

In the certified NPOESS program, CMIS has been descoped to MIS, which has not yet been defined in detail. Participants frequently commented that CMIS was adopted with no input from the scientific user community and with limited evidence of the capabilities of passive microwave for estimation of ocean surface vector winds. Regard-

less of whether MIS includes the polarimetric measurements required to estimate wind direction, it would result in a degradation of the accuracy, coverage, and resolution of ocean vector winds provided by QuikSCAT, especially in rainy conditions. Moreover, MIS would worsen the sampling of the wind field near land compared with QuikSCAT. MIS is therefore not a viable mitigation strategy for maintaining the ocean surface vector winds CDR.

India and China plan to launch scatterometers in 2008 and 2010, respectively. The instrument designs for these scatterometers are unknown and data availability remains uncertain for both missions. Neither of these scatterometers can therefore be considered viable mitigation strategies for continuation of the ocean surface vector winds CDR.

While QuikSCAT has provided many benefits and has established a baseline CDR for ocean surface vector winds, there are important limitations to the QuikSCAT data. For example, the Ku-band QuikSCAT radar cannot measure extreme winds or winds in heavy rain (although it can measure wind speeds of up to about 90 kt, if those winds occur outside of rain and are not confined to a very small area, both of which are the case in most hurricanes). QuikSCAT measurements are also limited to a spatial resolution of 12.5 km and are not routinely made closer than about 30 km from land. Many in the microwave breakout group argued that high priority should be given to a sustained, more capable, next-generation scatterometer program that can meet these requirements while at the same time continuing the ocean surface vector winds CDR established by QuikSCAT.

Since QuikSCAT is already 3 years past its designed instrument lifetime, it was a widely held view that continuation of the ocean surface vector wind CDR is in serious jeopardy. None of the currently operating or future planned instruments can continue the ocean surface vector winds CDR. Two mitigation scenarios were discussed. Both consist of a dedicated free-flyer scatterometer mission at the nearest possible opportunity in order to avoid, or at least minimize, a gap in the ocean surface vector winds CDR. This mission is envisioned as the first in a sequence of such missions.

Mitigation Scenario 1. The first scenario involves a QuikSCAT clone, which is the minimal solution for continuing the accuracy, resolution, and coverage of the 8-year ocean surface vector winds CDR established by QuikSCAT. The advantage is that a QuikSCAT clone is preliminarily estimated by NASA to be approximately 10 percent less expensive and could be readied 6 months sooner than the advanced scatterometer considered in the second scenario. The small percentage cost differential is because QuikSCAT is based on 1980s technology that would have to be updated to currently available electronic components. This updating would lead to a redesign of major instrument subsystems, thereby losing many of the cost advantages of a true "build-to-print" duplication of the QuikSCAT instrument. The disadvantage of a QuikSCAT clone is that some of the most important NOAA operational requirements established at the June 2006 NOAA Operational Ocean Surface Vector Winds Requirements Workshop²⁷ would not be met (e.g., measurements of extreme winds, higher spatial resolution, and reduced contamination from rain and land).

Mitigation Scenario 2. The second scenario, preferred by many participants, consists of a next-generation synthetic-aperture-radar-based scatterometer mission referred to in the Earth science decadal survey as XOVWM. XOVWM would include a dual-frequency Ku-band and C-band radar and an X-band radiometer, which would allow measurements in rainy conditions, as well as measurements of the extreme winds in hurricanes and extratropical cyclones. The next-generation system would provide measurements with a resolution of better than 5 km and to within 1-3 km of land. XOVWM would thus satisfy most of the NOAA operational requirements, while at the same time maintaining the ocean surface vector winds CDR established by QuikSCAT and beginning a more

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²⁶See "Oceans Community Letter," April 6, 2006, available at http://cioss.coas.oregonstate.edu/CIOSS/Documents/Oceans_Community_Letter.pdf.

²⁷The NOAA Operational Ocean Surface Vector Winds Requirements Workshop, held June 5-7, 2006, at the National Hurricane Center in Miami, Florida, was sponsored by the Office of the Federal Coordinator for Meteorology. The final report of the workshop is available at http://www.ofcm.gov/tcr/reference/Ocean%20Surface%20Vector%20Winds_ workshop_report_final.pdf.

accurate record of strong storms at sea, including hurricanes. The relatively minor disadvantages of XOVWM over a QuikSCAT clone are an approximate 10 percent cost increase (based on preliminary NASA estimates) and a 6-month longer delay to launch. The minor cost increase for XOVWM versus a QuikSCAT clone reflects the reality that even an attempt to duplicate the existing QuikSCAT would incur many of the nonrecurring costs of XOVWM, in part because of the long delay since QuikSCAT's initial development and the obsolescence or unavailability of the hardware components used. XOVWM is a mission recommended in the decadal survey; several workshop participants argued that the proposed schedule for launch of this mission—2013-2016—be accelerated. Finally, while discussing this mitigation scenario, some participants indicated the desirability of an enhanced XOVWM+SST mission, a point that was also made during day 1 discussions.

Geostationary Hyperspectral Measurements

GOES-R is being developed as NOAA's next generation of geostationary weather satellites. In late 2006, following large increases in estimates for completion of the program, NOAA canceled plans to incorporate a key instrument on the spacecraft—HES. HES was planned to provide both an advanced sounding capability for measurements of atmospheric temperature and moisture content and an imager for monitoring coastal water quality and assessing coastal hazards. Background on the HES instrument, along with a summary of the breakout participant discussions, is provided below.

Background

Geostationary sounders provide unique, rapidly updated moisture profile measurements. In 1980, through the Operational Satellite Improvement Program (OSIP), NASA and NOAA partnered to fly a critical demonstration mission—the Visible and Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS). VAS was the first atmospheric temperature and moisture profiler flown in GEO. Subsequent three-axis-stabilized operational GOES-I-class sounders significantly improved upon VAS's precision and have collected long-term records of atmospheric variables and diurnal cycles over the Western Hemisphere through the present time. These measurements will continue through the flight of the GOES-N/O/P series. With the termination of the GOES-R sounder, these long-term records will end.

The value of sounding from GEO, however, goes beyond maintenance of a long-term record. The ability to sense water vapor in the atmosphere is crucial for monitoring and predicting hazardous weather conditions. Large variations in atmospheric water vapor occur over fine scales of 10 km in the horizontal and 1 km in the vertical, and over tens of minutes; therefore, high-temporal-resolution monitoring is essential. The current GOES-N-class sounder temperature and moisture profiles provide relatively coarse temporal and spatial coverage, which is informative for indicating the synoptic-scale severe weather threat to areas, but insufficient for "nowcasting" cell development on the mesoscale or adequately resolving boundary-layer structures critical for nowcasts of severe thunderstorms.

Summary of Breakout Group Discussion

The GOES-R/HES breakout group session focused on mitigation options to restore the high-vertical-resolution temperature and water vapor sounding products and associated derived products planned for the HES payload on the GOES-R series. The breakout group did not address the coastal water imager because the ocean color community was not sufficiently represented. As noted above, the reader is advised that the options presented do not include all that might be considered, and that both the options and the analysis are necessarily the subjective and not always disinterested views of presenters and participants.

The breakout group heard a presentation regarding the importance that high-temporal-resolution hyperspectral observations of key atmospheric state variables and their trends have for climate data records. Such measurements are not easily made except from a geostationary orbit. The role of geostationary hyperspectral measurements in characterizing diurnal variations, identifying the sources, sinks, and transport of pollutants and greenhouse gases, and a potential key role in sensor intercalibration, ²⁸ were also discussed.

The case was then presented for advanced geostationary sounding capabilities as a contribution to GEOSS societal benefit areas, atmospheric ECVs, Numerical Weather Prediction capabilities improved by four-dimensional data assimilation, nowcasting capability, and sensor intercalibration.²⁹ The value of nonclimate applications of such measurements was emphasized.

A presenter then reviewed the NESDIS Office of Systems Development Analysis of Alternatives (AoA) study,³⁰ which considered a broad array of advanced geosynchronous sounder alternatives and trade-offs. The AoA study's conclusions were discussed, particularly the need for an advanced sounder and space-based technology demonstration as early as feasible. It was suggested that previous ground system cost estimates were driven up by the inclusion of the coastal waters imager and that a recent proposal by NESDIS/STAR,³¹ considering only the advanced sounder in a demonstration mode, reduced the cost estimates significantly from the original estimates. In addition, the presenter noted the similarities between the AoA and Earth science decadal survey recommendations, which endorse the need for (at reasonable cost and risk) an operational advanced imaging sounder for GOES and an early demonstration. GIFTS was then introduced as a potentially viable option to get a demonstration instrument into GEO as early as possible. The presenter suggested that if launch services could be identified, such a mission could be done for approximately \$150 million. This proposed track would not interfere with the GOES-R schedule but would retain the timing necessary to influence the design of the operational version for GOES-T. Concurrently, the presenter argued, reduced-capability advanced sounders should be developed for the GOES series.

Some attendees at the breakout group argued forcefully that an advanced sounder with HES-like capabilities would revolutionize short-term prediction, most notably of severe weather. Some workshop participants also referenced a NOAA/NESDIS-commissioned analysis of the potential economic benefits of the GOES-R ABI and HES instruments, ³² which supported the economic justification for a HES-like capability. Advocates for including HES-like capabilities on GOES-R, which in this self-selected breakout group seemed to be most of the attendees, were very displeased by the indication during a plenary presentation by a NOAA official that an advanced hyperspectral sounder was "off the table" for GOES-R/S, and would most likely be next considered as a demonstration instrument on GOES-T. Some participants suggested that NASA and NOAA partner to achieve earlier GEO hyperspectral sounder capability, taking advantage of the inherent strengths of both agencies (and reinvigorating the OSIP).

Mitigation Scenario 1. Scenario 1 involves use of simulated sounder products taking advantage of only ABI observations. Many participants considered this option to be generally undesirable, as ABI lacks spectral, and therefore vertical, resolution and would be unable to provide the many products expected from HES.

Mitigation Scenario 2. Scenario 2 involves adding CrIS/ATMS back to the early morning (05:30) NPOESS orbit

²⁸For example, geostationary hyperspectral sounders are identified as a key component of a Global Space-Based Inter-calibration (GSICS) system. See http://www.star.nesdis.noaa.gov/smcd/spb/calibration/icvs/GSICS/index.html.

²⁹P. Ardanuy, B. Bergen, A. Huang, G. Kratz, J. Puschell, C. Schueler, and J. Walker, "Simultaneous Overpass Off Nadir (SOON): A method for unified calibration/validation across IEOS and GEOSS system of systems," in *Atmospheric and Environmental Remote Sensing Data Processing and Utilization II: Perspective on Calibration/Validation Initiatives and Strategies* (A.H.L. Huang and H.J. Bloom, eds.), Proceedings of SPIE, Volume 6301, 2006.

³⁰NESDIS and OSD, Analysis of Alternatives, 2007. Participants in the AoA study included NOAA/NESDIS offices, university/cooperative institutes, contractors, DOD, and NASA.

³¹NESDIS/STAR (Center for Satellite Applications and Research) is the new name for the former Office of Research and Applications.

³²Centrec Consulting Group, LLC, An Investigation of the Economic and Social Value of Selected NOAA Data and Products for Geostationary Operational Environmental Satellites (GOES). GOES-R Sounder and Imager Cost/Benefit Analysis, NOAA/NESDIS, 2007. The economic analysis suggested that the inclusion of hyperspectral sounding capability in addition to ABI would nearly double the socioeconomic benefit of GOES-R from \$2.4 billion to \$4.3 billion.

platforms. This remanifesting would add a useful additional pair of diurnal observations that would provide hyperspectral information. It would not, however, approach the temporal refresh available from geostationary orbit.

Mitigation Scenario 3. Participants suggested a scenario involving an opportunity for an early demonstration of GEO hyperspectral capabilities by launching GIFTS on a near-term flight of opportunity (i.e., free flyer or international partnership) to advance user readiness and allow algorithm development. It was noted that savings in nonrecurring engineering would be lost with this approach, as the demonstration unit (i.e., GIFTS) would not be the same as subsequent units, requiring subsequent demonstrations. Flight of an engineering model (rather than GIFTS) as a demonstration was seen as a way to save on nonrecurring engineering costs. However, there were differences of opinion among the group on the question of whether it would be less expensive or more desirable to launch GIFTS, build a different early demonstration model, or build the first flight model of the desired sounder.

Mitigation Scenario 4. Another potential approach to retaining (and advancing) the sounder capabilities on GOES was presented by a representative of ITT Space Systems who argued that the ITT "ABX" sounder is a simpler approach that could bridge the gap between the GOES-N legacy sounder and a full hyperspectral sounder on GOES-T. For GOES-R, the ABX would involve 18 sounding channels by reducing the ABI scan rate to improve the signal-to-noise ratio. This could "evolve" into a full hyperspectral capability by GOES-T using the preplanned product improvement (P³I) track. This option would allow retention and enhancement of existing capabilities, provision of GIFTS-like bands, and the potential for extensive reuse for subsequent flights. The perceived negative aspect of this solution is that a full hyperspectral demonstration may be delayed until GOES-T. Other proposed GOES-R series sounder options and paths have been considered by industry; given the competitive nature of such options, however, the representatives at the workshop indicated that they were not at liberty to share the specifics.

Other Discussions. It was stated that much of the cost of HES was attributable to the ground system requirements of NPOESS, which are driven by latency requirements. However, according to participants at the breakout session, latency is not a large concern of the hyperspectral community. Thus, most participants also argued that the cost savings that could result from a relaxation of the latency requirement should be pursued. Indeed, the demonstration mode referred to by presenters largely implies relaxation of latency as a cost-savings strategy.

Due to session time limitations, the HES breakout group was not able to consider the merit of a HES Observing System Simulation Experiment (OSSE).³³ However, an expert on OSSEs provided a background handout for the group and suggested to the chair of the session that a mesoscale OSSE for the HES instrument could be extremely valuable if done correctly. However, it would require considerable development and a great deal of caution for the conclusions of such a study to be deemed credible. Such a mesoscale OSSE has, to the workshop participants' knowledge, never been done. Additional comments on the OSSE topic by European experts during the international videoconference session on day 3 suggested that the HES OSSE would be very difficult and likely not possible in a timely manner.

WORKSHOP SUMMARY—DAY 3

Plenary Session on International Considerations

On Thursday morning, the workshop held a joint international session, through videoconference, with participants at the World Meteorological Organization (WMO) "Workshop on the Re-design and Optimization of the Space-based Global Observing System" that was underway in Geneva, Switzerland. WMO workshop participants included high-level representatives of operational and research and development space agencies, the Committee on Earth Observations Satellites (CEOS), Global Climate Observing System (GCOS), the WMO Space Programme, the WMO Open Programme Area Group/Integrated Observing System (OPAG/IOS), and the Expert Team on Evolution of the Global Observing System (ET-EGOS). That workshop is expected to result in recommendations for both weather and climate monitoring from space being forwarded to the appropriate levels of WMO,

³³For details on OSSEs, see http://www.emc.ncep.noaa.gov/research/osse/.

the Coordination Group for Meteorological Satellites (CGMS), and CEOS. Anthony Hollingsworth (European Centre for Medium-Range Weather Forecasting; ECMWF) also participated in the videoconference from Reading, England.

WMO coordinates efforts for meeting the needs for climate information, such as for climate monitoring, climate-data management, climate-change detection, seasonal-to-interannual climate predictions, and assessments of the impacts of climate change. In the view of WMO representatives, measurements of the climate system should be considered as an operational requirement, and climate monitoring and climate measurements should be given equally high priority within the Global Observing System (GOS). In the WMO Rolling Review of Requirements process, climate requirements are represented by the GCOS Implementation Plan. The WMO presentation noted that taken as a whole, there has not been a concerted strategy for sustained climate observations from space. Instead, the climate community has relied on suboptimal sensors to create a climate record, resulting in significant challenges in terms of handling bias differences, orbit drift, data gaps, and spectral differences between follow-on instruments when reprocessing multiple-satellite data—often at considerable cost.

The CEOS presentation provided valuable insight into how various thematic issues could be addressed on a global basis utilizing the CEOS constellation concept, which considers virtual constellations of research and operational satellites to meet observational needs. Study teams have been established and international cooperation among space agencies has been stimulated to explore four representative Constellation prototypes, including atmospheric composition, global precipitation, land surface imaging, and ocean surface topography. It was noted by several speakers that the impact of NPOESS descoping was immediately significant in terms of GOS/GCOS planning and the quality of the CDRs for several variables.

The Global Monitoring for Environmental Security (GMES) and climate modeling presentation addressed key uncertainties identified by the IPCC Fourth Assessment report,³⁴ global satellite provisions for atmospheric composition in the 2003-2019 time frame, European launch plans for 2007-2015, the GMES Sentinel program, and progress on the Global and regional Earth-system (Atmosphere) Monitoring using satellite and in situ data (GEMS) atmosphere project at ECMWF.

The need for hyperspectral observations from geostationary satellites was also addressed, including a discussion of their potential role in calibration of the space-based observing system (within those spectral ranges); monitoring of the diurnal cycle; and provision of spectrally resolved radiances (hyperspectral visible/near-IR and IR) as a climate reference.

Barbara Ryan, U.S. Geological Survey, reminded the teams that CEOS was strongly promoting an integrated observing system that included in situ data for ongoing verification and validation of satellite observations. In situ data are essential and complementary to the space segment data streams, enabling long-term monitoring of satellite data quality and as an independent component of the long-term climate record.

A number of other important considerations were brought forth during the videoconference. The importance of sustaining climate-quality climate data from space was addressed, along with the need to keep valuable space assets in operation after they have passed their design lifetime (e.g., Terra, Aqua, and Aura, which provide data for a variety of applications). There was recognition of the importance of determining how to preserve the heritage of past and current instruments with the natural evolution to advanced future instruments for extending climate records. It was further recognized that with limited financial and human resources, a response to GCOS requirements can be achieved only through enhanced international cooperation. Such cooperation should involve global planning with international contributions, in such a way that implementation problems encountered by an individual agency do not dramatically affect the global system. It was recognized that a number of missions planned in Europe will be of great value for climate analysis and that there is an acute need for better international collaboration and awareness spanning the full spectrum of activities from high-level data access agreements to pragmatic documentation exchange.

Concerning the NPOESS configuration, many participants supported:

³⁴Intergovernmental Panel on Climate Change, *Climate Change 2007*, IPCC Fourth Assessment Report, Cambridge University Press, Cambridge, U.K., 2008, available at http://www.ipcc.ch/ipccreports/assessments-reports.htm.

- 1. Remanifesting hyperspectral IR and microwave sounders in the early morning orbit—both for operational purposes and for reanalysis and climate-related activity.
- 2. Maintaining continuity of microwave SST measurements at 6.9 GHz (AMSR-E type). With the loss of CMIS on C1 and increasing concern regarding the health of the AMSR-E on-board Aqua (indications of a failing antenna bearing), there is a significant risk of a microwave SST data gap prior to the launch of the Japanese GCOM mission; this could be addressed by the future MIS.
- 3. Maintaining a high-precision Jason-type altimeter in non-Sun-synchronous orbit (to mitigate the impact of tidal aliasing on sea level measurements) complemented by at least two other altimeter missions (Sentinel-3 will be one) in a Sun-synchronous orbit. This was stated as an urgent need by many participants.
 - 4. Flying a CERES-class instrument for continuity of Earth radiation budget measurements.
 - 5. Accelerating development of an active vector wind mission to replace QuikSCAT.

Finally, during the closing plenary session, there was discussion again of the requirements for constructing, managing, and maintaining CDRs. As in previous sessions, participants discussed the intellectual and resource challenges in developing CDRs, which require attention and adequate budgets in the space segment, ground segment, and CDR production units themselves. It was noted that at present, the last is often limited in resources so that problems with satellite data are only discovered following dedicated ad hoc CDR processing projects. Some participants stated that considerable cost benefits would almost certainly be realized if CDR processing could be sustained in an operational near-real-time-style environment.

A general theme of the videoconference echoed the need for organizations to work together with synergies among international satellite programs and the importance of multilateral agreements in addressing climate monitoring. In the future, it is through effective international cooperation and global partnerships that useful climate monitoring from space will be realized. A frequently expressed sentiment was that the joint Geneva-Washington session was extremely important in terms of bringing the international satellite climate community together and that such communication should be encouraged through future meetings.

Breakout Sessions

The breakout groups on day 3 were loosely organized to enable participants to offer comments. Two panels were given specific topics, namely, to assess the NASA-NOAA suggested mitigation options and to further explore the intricacies of CDR development. These two breakout sessions are summarized here. A third breakout session allowed participants to comment on any topic within the scope of the workshop, and key points have been integrated into this report where relevant (many are covered in Chapter 3) and will be considered further during a follow-on study.

Panel to Assess NASA-NOAA Mitigation Options

The breakout panel reviewed a summary (see Appendix C) of the draft NASA-NOAA white paper titled "Mitigation Approaches to Address Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Goals." The Office of Science and Technology Policy (OSTP) had asked NOAA and NASA to provide this analysis of possible options for mitigation of the climate research impacts of the NPOESS Nunn-McCurdy certification through 2026, along with an assessment of the potential costs of these options, with the primary goal of ensuring the continuity of long-term climate records. The primary goal of the NASA-NOAA white paper was to identify means for ensuring the continuity of long-term climate records.

NASA noted that the white paper was based on a single sentence from the June 5, 2006, Nunn-McCurdy Acquisition Decision Memorandum: "[The restructured program] does not include funding for the following

³⁵Joint NASA-NOAA Study for OSTP (Phase II), June 19, 2007. The report does not consider GOES-R.

BOX 2.1 Generation of Climate Data Records

The instruments and data system for NPOESS are designed to produce a number of operational geophysical products, which are called environmental data records (EDRs). EDRs are generally produced by applying an appropriate set of algorithms to raw data records. Although NPP- and NPOESS-derived EDRs may have considerable scientific value, climate data records (CDRs)^a are far more than a time series of EDRs. Participants at the workshop emphasized the fundamental differences between products that are generated to meet short-term needs (EDRs) and those for which consistency of processing and reprocessing over years to decades is an essential requirement.

Climate research and monitoring often require the detection of very small changes against a naturally noisy background. For example, sea surface temperatures can vary by several degrees between daytime and night-time, or from year to year, whereas the climate signal of interest may change by only 0.1 K over a decade. Moreover, changes in sensor performance or data-processing algorithms often introduce artificial noise that may be greater than the climate signal. In addition to natural and artificial noise, spatial and temporal biases in the measurements confound climate researchers. A CDR suitable for studying interannual to decadal climate variability and trends includes a time series produced with stable, high-quality data, and error characteristics that have been quantified by accounting for all of the above sources of error and noise. The production of a CDR requires considerable refinement of the raw data and the blending of multiple data streams. These streams may come from multiple copies of the same sensor, or they may be ancillary data fields that are used in synergy with the primary data stream. Thorough analysis of sensor performance and improved processing algorithms are also required, as are quantitative estimates of spatial and temporal errors. Figure 2.1.1 illustrates the notional pathways that result in generation of an EDR and a CDR.c

The past experience of the climate research community with the Microwave Sounding Unit (MSU) and Advanced Microwave Sounding Unit (AMSU) provides a constructive case study in the challenges associated with constructing CDRs with satellite data. Starting in late 1978, nine polar-orbiting satellites carried identical copies of the MSU to measure atmospheric temperatures. In a 2000 National Research Council report, ^d it was noted that the last MSU occupied the afternoon orbit slot (NOAA-14), while the morning slot was monitored by the AMSU on NOAA-15. ^e Constructing CDRs from MSU instruments revealed that even though the prelaunch instruments were essentially identical, postlaunch differences among them were as large as the climate signal being sought. Once in space, each was found to have a unique response to variations in direct solar heating. Others experienced shifts in responses to onboard calibration targets. Another was found, after launch, to have been improperly calibrated in the laboratory. A final complication was due to the fact that the frequencies monitored with the new AMSU were slightly different from those monitored with the legacy MSUs. Scientists who were interested in stable, long-term temperature records from the MSU were required to commit considerable resources to discover the aforementioned problems and to test adjustments.

A similar example is seen in the generation of sea surface temperature CDRs. Sea surface temperature (SST) CDRs were improved through several joint agency efforts (e.g., NOAA-NASA Pathfinder program) and, more recently, merging of complementary infrared and passive microwave satellite data having global daily coverage together with in situ observations as part of the international Global High Resolution SST Pilot Project (GHRSST-PP). The GHRSST-PP is also pioneering the development of a high-resolution SST CDR within a dedicated reanalysis project, led by the NOAA's National Oceanic Data Center, for the satellite era (1981-present).

Calibration and validation in the context of CDRs can be considered a process that encompasses the entire system, from sensor to data product. 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.

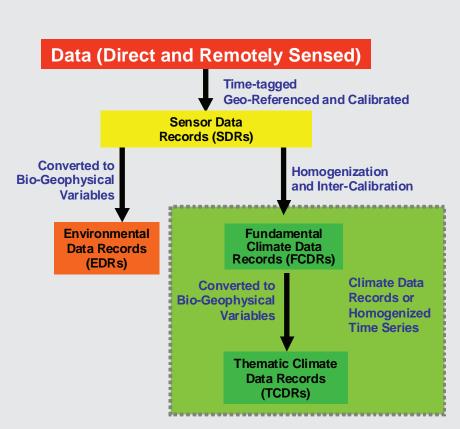


FIGURE 2.1.1 Pathways in the development of EDRs amd CDRs. SOURCE: J.J. Bates, NOAA National Climatic Data Center, "NPOESS EDRs vs. Climate Data Records (CDRs)," presentation to the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft, April 23, 2007.

^a See National Research Council (NRC), *Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites*, National Academy Press, Washington, D.C., 2000, and NRC, *Climate Data Records from Environmental Satellites: Interim Report*, The National Academies Press, Washington, D.C., 2004.

^b Robust climate data records rely on the complementary nature of seemingly duplicate observations. For example, highly accurate and high-resolution infrared SST observations are confounded by the presence of clouds, whereas coarser-resolution passive microwave SST observations are able to measure SST through clouds. By combining synergistic use of the two data streams, the CDR can be improved.

^c From J.J. Bates, NOAA National Climatic Data Center, "NPOESS EDRs vs. Climate Data Records (CDRs)," presentation to the panel on April 23, 2007.

^d NRC, Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites, 2000.

^e NOAA 14 was decommissioned on May 23, 2007.

^f Proceedings from the Fourth GODAE High Resolution SST Pilot Project Workshop, Pasadena, Calif., Sept. 22-26, 2003. GHRSST-PP Report No. GHRSST/18 GODAE Report No. 10. Available at http://dup.esrin.esa.it/files/project/131-176-149-30_20068812258.pdf. More general information about GHRSST is available at http://www.ghrsst-pp.org.

sensors: APS, TSIS, OMPS-Limb, ERBS, ALT, SuS, and the full SESS; however, the program will plan and fund for integration of these sensors onto the satellite buses, if the sensors are provided from outside the program."³⁶

The options presented in the draft white paper represent a departure from the traditional NPOESS/EOS/MetOp big-platform approach. They are a combination of NPOESS operational flights, accommodations of opportunity, and "climate free flyers." These focused missions would be dedicated to a limited number of specialized sensors; simpler instruments could have dedicated functions (e.g., to separate reflective from emissive bands). The apparent intent is to use a constellation approach to obtain as many complementary measurements as possible through formation flight.

The panel was encouraged by the imagination shown by the NASA-NOAA team and was extremely supportive of their ideas for implementation flexibility—specifically including flights on diverse platforms, including formation flight with NPOESS. However, the white paper options focused on only five instruments: TSIS, ERBS/CERES, ALT, OMPS, and APS. NASA noted that the white paper does not consider mitigation options for VIIRS, CrIS/ATMS, CMIS/MIS, and SESS. Some workshop participants commented that the lack of attention to the other instruments should not be construed as a de facto lower prioritization of their suitability as options for mitigation of lost capabilities. NASA and NOAA will expand the white paper options to consider the other sensors that will fly, revising the white paper based on comments from this workshop. They plan to deliver a revised draft to OSTP by late summer.

Panel on Issues Related to CDR Development

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Underemphasized during certain sessions of the workshop, but recognized as fundamental for ensuring the climate record from space, is the technical issue of generating the needed CDRs from the operational EDRs. Crucial issues include the accommodation of ancillary observations critical for CDRs but absent from the current and planned satellite systems, and the ability to adequately develop and maintain CDRs. The breakout session considered requirements for CDRs (particularly in contrast to EDR retrievals) and the adequacy of current (post-Nunn-McCurdy) plans for prelaunch instrument calibration and characterization; on-orbit calibration and validation; measurement overlap and replenishment requirements; and data storage, archiving, distribution, reprocessing, analysis, and interpretation concerns.

Presenters and many participants at the breakout session echoed a concern that the fundamental definitions of EDRs and CDRs and the requirements for CDR generation and maintenance are not adequately understood by the operational and research community. Proper communication of requirements for CDRs requires that these distinctions be clearly understood. According to presenters from the NOAA National Climatic Data Center, even though the sensor signals used to generate EDRs are also used for CDRs, the EDRs themselves are frequently of little use for climate research. EDRs are (in general) poorly calibrated, quick-turnaround products that lack long-term repeatability, whereas CDRs are fully calibrated time series having high precision (repeatability) and accuracy, often requiring reprocessing of entire data sets as algorithms are improved (Box 2.1).

Many participants noted that CDR science teams are crucial for maintaining the CDRs over many years (climate change time scales are long compared with those for weather), a task that is expected to require additional research, analysis, and validation of the observations (and thus funding, well beyond that applied to the EDRs). Prelaunch calibration and characterization that meet EDR requirements do not always (typically) meet the more exhaustive requirements for CDR accuracy and stability. Data-handling requirements are also completely different from those for EDRs and will likely require an independent CDR system.

Whereas functionally the EDRs are short-lived operational products, the CDRs must be permanently stored and continuously accessible for considerable additional ongoing research and analysis if they are to be of use in climate change policy making and societal applications. Given that data requirements for CDRs can exceed those for EDRs, a list of missing data should be developed and considered as part of the mitigation option analysis.

³⁶Under Secretary of Defense for Acquisition, Technology and Logistics, Acquisition Decision Memorandum, dated June 5, 2006, Office of the Secretary of Defense, Washington, D.C.

3

Cross-Cutting Issues

A number of issues were mentioned in multiple workshop plenary sessions or breakout groups and are thus included here as cross-cutting issues. A detailed treatment of any of the issues is beyond the scope of the workshop; however, summaries are included here for completeness.

SYNERGY VERSUS COMPETITION WITH DECADAL SURVEY

As noted in the statement of task for the workshop, NPOESS/GOES-R mitigation strategies should take into account the plans for execution of the recent National Research Council (NRC) Earth science decadal survey. However, it is important to note that the decadal survey covers all of Earth science, including, but not limited to, climate science. Discussions at the workshop focused on climate science; however, the ultimate implementation of NPOESS/GOES-R climate observation mitigation will occur in parallel with NASA's intent to implement a balanced Earth science program. This will be challenging, particularly because of the very constrained Earth science budget at NASA. As highlighted in the NRC decadal survey report, Earth science budgets have declined significantly in real-year dollars, while mission costs have risen, due to large increases in launch costs, the unanticipated effects of full-cost accounting, and inflation, and as demand for and reliance on Earth science remote sensing observations have continued to increase. Some workshop participants noted that NASA and NOAA will be greatly challenged to find the appropriate balance between maintaining continuity of key climate parameters and continuing to advance Earth science; these participants also argued that this cannot be an "either/or" decision.

It was frequently noted that one way to address the challenge of balance between measurement continuity and scientific advance was to consider areas of potential synergy between options for climate observation mitigation and missions recommended by the decadal survey. As the decadal survey mission concepts mature, these synergies could be further explored to determine areas where synergy—rather than competition for scarce resources—exists.

CONTINUITY OF LONG-TERM RECORDS VERSUS NEW MEASUREMENTS

Just as climate science is one part of Earth science, so also are sustained measurements but one part of climate science. At the workshop, there was discussion regarding the need to find a balance between providing for conti-

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

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nuity of certain key long-term climate records and advancing climate science through taking new measurements to elucidate key climate processes and initialize climate models. Again, this is not an "either/or" decision, and finding the proper balance between sustained and new measurements will be challenging.

Starting with the evident proposition that the climate science program cannot afford to continue all, or even many, remote sensing measurements indefinitely, participants sought to distinguish between measurements that represent state variables that are so fundamental that they must be continued in perpetuity and those that are valuable and have shorter-term measurement campaigns. The list of state variables should be as short as practical to allow for sustained funding commitments without overwhelming the already-limited budget and precluding new or improved measurements critical to advancing climate science. One suggestion was for implementation of a peer-review process that would periodically review the list of essential variables to consider the science justification for continuation of each sustained record, keeping the list to the minimal measurement set practical.

MEASUREMENT TEAMS

The need for sustained attention to the establishment and maintenance of climate data records (CDRs), which can involve many missions over many decades, led numerous workshop participants to suggest the need for climate measurement teams, independent of mission science teams.

CALIBRATION AND CHARACTERIZATION (PRE-, IN-, POST-FLIGHT)

During the workshop it came to the attention of participants that all subsequent flight builds of the various NPOESS instruments were not planned to undergo the extensive preflight characterization expected for the first builds. Many participants felt it was essential to urge continuation of a rigorous preflight testing and characterization program with subsequent flight builds, and to request improved documentation to increase the climate science utility of data returned from later NPOESS platforms (to date this is not currently planned). Preflight characterizations would ensure that the sensors are stable, as nearly identical as possible from sensor to sensor, and thus climate relevant.

FORMATION FLYING

Some participants at the workshop discussed the advantages of formation flying and how this concept, demonstrated on the Earth Observing System "A-Train," might affect mitigation options in the future (Figure 3.1). The principal benefit of formation flying is the ability to combine multiple, synergistic measurement types without incurring the cost, complexity, and risk of large monolithic observatories—as long as sufficient pointing and position knowledge are achieved and orbits are sufficiently maintained. There are, of course, operational challenges associated with formation flight (e.g., maneuver coordination, orbit insertion, and end-of-life considerations), although these can be minimized through careful plans and procedures and by taking advantage of the lessons learned through NASA's A-train operations. It was suggested by some participants that NASA and NOAA fully consider formation flying, including the requisite orbit maintenance and operations requirements, as a deliberate part of the mitigation strategy for restoring deleted NPOESS and GOES-R climate-observing capabilities.

STABILITY REQUIREMENTS PARTICULAR TO CLIMATE STUDIES

It was noted that even when there is perceived synergy between climate research and operational needs based on resolution, care must be taken in assessing the stability requirements that are unique to long-term trend studies and that can drive instrument design costs dramatically.

INTEGRATION ON NPOESS VERSUS FREE FLYERS: LARGE VERSUS SMALL PROGRAMS

Small programs often can succeed with a leaner systems engineering and management approach than can larger programs. Given the large national investment already made in NPOESS, agency commitments to allow for

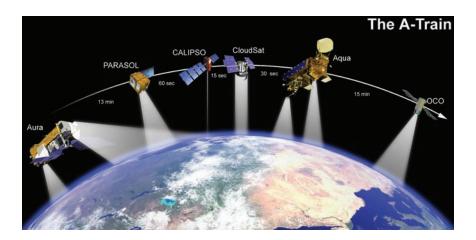


FIGURE 3.1 Artist's conception of the A-Train. The A-train satellites are, from left, Aura, PARASOL, CALIPSO, CloudSat, Aqua, and the Orbiting Carbon Observatory (OCO), which will lead the formation after its planned launch in 2008. SOURCE: NASA, Washington, D.C. Available at http://www.nasa.gov/mission_pages/cloudsat/multimedia/a-train.html.

remanifesting of canceled instrument payloads, and spacecraft margins that include on the order of a metric ton of mass, kilowatts of power, millions of bits per second of spare bandwidth, and large, unused parts of the optical bench, it is natural to consider NPOESS platforms for the flight of climate-relevant sensors. However, based on presentations from the agencies to the workshop, it appears that the incremental cost of the accommodation (integration and test, with management and systems engineering overheads) might equal or even significantly exceed the total cost of a free-flyer accommodation. The lack of a cost-effective process for integrating climate payloads onto NPOESS, given the significant investment in developing the capacity to fly the payloads once integrated, is a significant impediment in terms of low-cost access to space.

Because of the extraordinarily high cost of integration with NPOESS, free flyers appear to be no more expensive, and may even be cheaper, than reintegrating the demanifested sensors into the existing NPOESS bus. The use of free-flying spacecraft to ensure the continuity of CDRs was frequently suggested as desirable by workshop participants. Free flyers provide increased launch flexibility, which decreases the risk of a gap in the measurements. It was considered noteworthy that none of the climate sensors are considered of sufficiently high priority for sensor failure to trigger the launch of a new NPOESS bus to preserve the data record. However, free flyers are not without risk, as they are typically more susceptible to cancellation compared with a single large, operational spacecraft bus. Some participants also noted that regardless of their desirability, NOAA has no history of utilizing free flyers as operational space platforms.

STRUCTURAL ISSUES ASSOCIATED WITH PROCUREMENT OF SENSORS THAT SUPPORT CLIMATE SCIENCE

Lack of an Enterprise View

Progress in climate research depends on continuous, multidecadal time series measurements for a stable underpinning as well as new measurements to advance process understanding. However, it often appears that the United States lacks such a fundamental enterprise view² for the maintenance and stewardship of a climate observing system. Some workshop participants noted that communication between NASA and NOAA appears to be improving; however, there was continuing concern because the agencies have yet to demonstrate a pragmatic

²A purposeful undertaking, especially one of some scope, complication, effort, boldness, and risk, as defined in the *American Heritage Dictionary of the English Language*, Fourth Edition, Houghton Mifflin Company, 2004; WordNet® 3.0. Princeton University, July 8, 2007.

success-oriented process that seamlessly ties together cutting-edge research demonstrations with continuity of operational measurements.

In the view of many participants, critical and unique measurement time series, such as that for over-ocean near-surface vector winds, are placed at risk through the lack of a planned transition when an existing instrument (e.g., QuikSCAT) ages and ultimately fails. Not only are improvements to existing Western Hemisphere geosynchronous atmospheric temperature and moisture profiles deferred, but the measurements themselves are also eliminated, due to a lack of agility in the block procurement process. When operational budgets are tight, there is a temptation for NOAA to declare relatively new but demonstrated capabilities (e.g., hyperspectral soundings) as "demonstrations" and then look to NASA for the funding. Similarly, NASA has indicated it would like NOAA to fund the cost of extended research missions that have operational utility. Developing a more effective national and international climate observation enterprise would greatly benefit climate science. Some participants mentioned the Earth science decadal survey recommendation, directed to the Office of Science and Technology Policy, which calls for a national plan to provide for sustained Earth observations.³

Proprietary Nature of Industry Contracts

The competitive process, properly executed, can yield better-value products and services that may be of higher quality, and lower risk and cost, than those obtained through sole-source acquisitions. Industry invests to obtain, retain, and increase competitive advantages—and so do nations. Much of the climate observing and remote sensing technology has multiple uses. Thus, there is an understandable need to safeguard proprietary intellectual property, and a corresponding need to safeguard the purity of the procurement process. The combined protections of International Traffic in Arms Regulations, brown-outs and black-outs associated with government procurements, firewalls to separate programs and people, and competitive pressures combine to create a significant obstacle to the sharing of sensor information, and they stifle the collaboration of industry, government, academia, and nations in climate observations. Creating mechanisms for collaboration and partnership could greatly benefit climate science. For example, one of this report's reviewers noted the progress made within the IOCCG, OSTST, and GHRSST-PP in both operational system development and reanalysis.

Minimal Insight into Algorithm Development

Algorithms and science applications represent the intellectual core of the process that turns sensor observations (inputs) into climate, weather, and other environmental products and services (outputs)—and ultimately socioeconomic benefits. Developing improved algorithms that go beyond today's state of practice requires individuals with a deep intellectual background in specific science disciplines. For example, every improvement in spectroradiometric quality (e.g., an increase in the "bit depth" of an observation from 8, to 10, to 12, to 14 bits), while providing new abilities to resolve phenomena of interest, also creates the need for improved algorithms that untangle the desired signal from the environmental "noise."

Many participants stated that it is critical that communities of interest, often government-academic-contractor teams with careers spent in the field, be at the center of the algorithm development process. When systems are procured in a turn-key fashion, decisions are often dominated by the highest-cost and highest-schedule-risk items (e.g., spacecraft, launch, sensor, computing system). As a consequence, a less-than-optimal algorithm development solution may be selected without community input or oversight. When algorithm development becomes decoupled from the communities of interest and practice, higher-cost, higher-risk, and lower-performing solutions can be unintended but unavoidable consequences. While recognizing that algorithms must be reliably implemented and maintained as operational code, ensuring maximum insight, oversight, participation, and leadership of the most relevant science communities could greatly benefit climate science.

³NRC, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, The National Academies Press, Washington, D.C., 2007, p. 14.

Appendix A

Statement of Task

In January 2007, the SSB Earth science decadal survey committee delivered to agency sponsors a prepublication version of its final report, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.* However, prior to delivery of the report, NASA and NOAA requested that additional tasks be added to the survey statement of task. The new tasks focus on recovery of measurement capabilities, especially those related to climate research, which were lost as a result of changes in plans for the next generation of polar and geostationary environmental monitoring satellites, NPOESS and GOES-R. It was mutually agreed that the new tasks would be addressed in a separate, follow-on report that would draw on the results of a major workshop. The new tasks are as follows:

- Analyze the impact of the changes to the NPOESS program that were announced in June 2006 and changes to the GOES-R series as described in the NOAA testimony to Congress on September 29, 2006. These changes included reduction in the number of planned NPOESS satellites, the deletion or descoping of particular instruments, and a delay in the planned launch of the first NPOESS satellite. In addition, recent changes to the GOES-R series resulted in deletion or descoping of instrumentation and a delay in the first spacecraft launch. The committee should give particular attention to impacts in areas associated with climate research, other NOAA strategic goals, and related GEOSS/IEOS societal benefit areas. The analysis should include discussions related to continuity of existing measurements and development of new research and operational capabilities.
- Develop a strategy to mitigate the impact of the changes described in the item above. The committee will prioritize capabilities that were lost or placed at risk following the changes to NPOESS and the GOES-R series and present strategies to recover these capabilities. 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 changes to the NPOESS and GOES-R programs may also offer new opportunities. The committee should provide a preliminary assessment of the risks, benefits, and costs of placing—on NPOESS, GOES-R, 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.

NOTE: Subsequent discussions with agency sponsors resulted in agreement to perform these tasks in two parts. Part I would consist of a workshop that would inform a subsequent study that would include panel findings and recommendations regarding mitigation strategies. The second part of the study will be completed in early 2008.

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Appendix B

Workshop Agenda

JUNE 19, 2007

Morning Plenary Session

Context Setting
Present Status of NPOESS and GOES-R
In-depth Discussion of Phase 2 Government Study

7:50 a.m.	Welcome
8:00	Teleconference with Mary Kicza and Mike Freilich (CEOS Meeting in Frascati)
8:30	Background and Overview for the Workshop— Organizing Panel Chair Antonio Busalacchi, University of Maryland
9:15	Review of the NASA-NOAA OSTP Re-manifest Phase 2 Study
	Sensor and Measurement Recovery Options—B. Cramer, NASA Headquarters CDR Science Support—J. Privette, NOAA NCDC
	Discussion
12:00 p.m.	Working Lunch: Overview of Relevant Decadal Survey Recommendations— Berrien Moore, University of New Hampshire

1:30 Breakouts (focus on ECVs)

Charge to the day 1 breakout groups: Each of the afternoon working groups will provide a short report that will be presented the following day in plenary session.

- 1. What are the priority space-based ECVs/climate data records under consideration by this breakout?
- 2. What subset of the above will be accommodated by the coordinated NASA-NOAA strategy as presented in the phase II NASA-NOAA remanifest study?
- 3. Are there alternative approaches that are not explored in the NASA-NOAA study (e.g., free flyers, alternative platforms, leveraging international partners)?
- 4. Assess the risks and benefits of these various options.
- 5. Document your results in the template that will be distributed at the meeting.

Some of the issues to be considered in the above:

- History/limitations of extant database and measurement capabilities, including calibration limitations and needs
- 2. How well alternative, indirect measurements or models can compensate for the lack of direct observations
- 3. Issues for interpreting the climate record—simultaneity of observations in time and space of related geophysical variables; spatial, altitudinal, and temporal resolution for each of the sensors, e.g., free flyers
- 4. Long-term strategy for ensuring climate records and broader climate services vision—overlap, calibration, redundant measurements/validation, data processing/reprocessing, algorithm development/evolution, archiving, science teams, grants/funding programs to support science teams

Breakout Session 1—Consideration of NPOESS and GOES-R Priority Measurements for ECVs/Climate Data Records Related to Observations of the Atmosphere

Tom Vonder Haar, Colorado State University; John Bates, NCDC

Rapporteur: Mark Schoeberl, GSFC

Breakout Session 2—Consideration of NPOESS and GOES-R Priority Measurements for ECVs/Climate Data Records Related to Observations of the Oceans

Bob Weller, invited; Jeff Privette, NCDC Rapporteur: Ralph Milliff, NWRA

Breakout Session 3—Consideration of NPOESS and GOES-R Priority Measurements for ECVs/Climate Data Records Related to Observations of the Land

Berrien Moore, University of New Hampshire; Marc Imhoff, GSFC

Rapporteur: Compton Tucker, CCSP

4:30 Workshop Adjourns for Day

JUNE 20, 2007

8:30 a.m.	Report out of Day 1 Breakouts
	40 minute sessions (20 presentation/20 discussion) on status and/or potential tradespace for NPOESS and GOES-R sensors related to:
9:30	Radiation Sensors and Climate—Stan Schneider, NPOESS IPO
10:10	Visible/IR Sensors Related to Climate—Steve Mango, NPOESS IPO
11:00	Microwave Sensors and Climate—Karen St. Germain, NOAA NESDIS
11:40	GOES-R/HES—Mark Mulholland, NOAA NESDIS
12:30 p.m.	Working Lunch—Jim Gleason, GSFC; Marc Imhoff, GSFC Discussion on the role of instruments on NPP and EOS (extended phase operations) in gap filling strategies
1:30	Breakouts (focus on sensors)

Session 1: Radiation Sensors

Judith Lean, NRL; Bruce Wielicki, LaRC

Rapporteur: Jim Coakley, Oregon State University

Total Solar Irradiance Sensor—Tom Woods, LASP Earth Radiation Budget Sensor—Bruce Wielicki, LaRC Ozone Mapping and Profiler Suite Limb Subsystem—Mark Schoeberl, GSFC

Discussion

Session 2: Visible and Infrared Imagers-Sounders

Graeme Stephens, Colorado State University; Paul Menzel, University of Wisconsin Rapporteur: Stacey Boland, JPL

MODIS and VIIRS—Carl Schueler, Raytheon SBRC (retired)
APS and APS-MODIS/VIIRS Synergy—Brian Cairns, GISS
AIRS/IASI/CrIS-ATMS Climate Considerations—Tom Pagano, Jet Propulsion Laboratory

Discussion

Atmospheric Climate Variables and CDRs—Paul Menzel, University of Wisconsin Land Climate Variables and CDRs—Compton Tucker, CCSP Ocean Climate Variables and CDRs—Chuck McLain, GSFC; Craig Donlon, U.K. Met Office

Session 3: Microwave Sensors

Frank Wentz, RSS; Dudley Chelton, Oregon State University

Rapporteur: Judith Curry, Georgia Tech

CMIS/MIS—Chelle Gentemann, RSS

ALT—Lee-Lueng Fu, Jet Propulsion Laboratory

QuikScat Follow-on and XOVWM/Other Options—Zorana Jelenak, NOAA/NESDIS

Discussion

Session 4: GOES-R and HES

Chris Velden, University of Wisconsin; Bill Smith, Hampton University Rapporteur: Phil Ardanuy, Raytheon

GOES-R and Its Role in Climate Research—Bill Smith, Hampton University Options to Restore HES Capabilities—Hank Revercomb, University of Wisconsin; David Crain, ITT

Critique of the NOAA Analysis of Alternatives Document—Bob Atlas, NOAA GIFTS and Its Potential Role in a Mitigation Strategy—Bob Atlas, NOAA Science Validation Using Observation System Simulated Experiment—Bob Atlas, NOAA

Discussion

4:30 Workshop Adjourns for Day

JUNE 21, 2007

Plenary Session

8:00 a.m. Report out of Day 2 Panels

9:00 International Dimensions of a Mitigation Strategy—Videoconference, Geneva (WMO Workshop, "Redesign and Optimization of the Space-Based Global Observing System"), Frascati, Italy (CEOS meeting), and ECMWF (Tony Hollingsworth)

Introduction of the Panel—Jim Purdom

Context of the NRC Panel on Options—Antonio Busalacchi

GOES-R Hyperspectral Measurements for Climate—Paul Menzel/Jim Purdom

CEOS Strategy on Climate Observations from Space—Barbara Ryan

WMO Workshop on Optimization—Don Hinsman

GMES and Climate Modeling-Tony Hollingsworth

Closing Remarks—Jim Purdom

Panel Questions and Discussion

Closing Remarks—Jim Purdom and Antonio Busalacchi

146	REPRINTED WORKSHOP REPORT
12:15 p.m.	Working Lunch
1:30	Breakouts
	Panel to Explore Particular Mitigation Options in Need of Further Analysis
	Panel on Issues Related to CDR Generation
	Review Requirements for CDRs (contrast with data retrievals for weather) and Assess Adequacy of Current, Post-Nunn-McCurdy Plans for: • Pre-launch Instrument Characterization and On-orbit Calibration/Validation • Overlap and Replenishment Requirements • Data Storage, Archiving, Distribution, and Reprocessing
	Panel-of-Panels Synthesis (What's been lost; what can be recovered; and, per NASA request, interplay with decadal survey recommendations)
4:00	Reconvene in Plenary Session
5:30	Workshop Adjourns

Appendix C

Mitigation Approaches Presented by NASA and NOAA at the Workshop

Mitigation Approaches to Address Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals

Joint NASA-NOAA Draft Study for OSTP (Phase II) June 19, 2007

Executive Summary [p. 2]

- OSTP requested NOAA and NASA to provide:
 - An analysis of possible mitigation options of the climate impacts of the NPOESS Nunn-McCurdy Certification through 2026
 - An assessment of the potential costs of these options
- Primary goal: Ensure continuity of long-term climate records
- NOAA and NASA analyzed the following options:
 - Remanifesting the climate sensors on NPOESS spacecraft
 - Placing sensors on currently planned non-NPOESS spacecraft
 - Developing new gap-filling climate satellite missions
 - Partnering opportunities
- Key results:
 - Work in progress: still assessing options
 - Multiple options exist to mitigate the loss of sensors from NPOESS
 - Options consistent with Decadal Survey recommendations
 - Partnering for altimetry could provide significant cost savings

NOTE: B. Cramer, NASA Headquarters, "Mitigation Approaches to Address Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals. Joint NASA-NOAA Draft Study for OSTP (Phase II)," presentation to the Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft Workshop, June 19, 2007, available at http://www7.nationalacademies.org/ssb/SSB_NPOESS2007_Presentations.html. The presentation as delivered at the workshop has been reformatted somewhat for publication. Page numbers in brackets refer to the original presentation. All information presented is pre-decisional, and assessments involve preliminary rough-order-of-magnitude cost estimates only.

Climate Sensor Impact Assessment (summarized from January 2007 NASA/NOAA Joint Assessment) [pp. 3-4]

- Total Solar Irradiance Sensor (TSIS)
 - Essential to discriminate between natural and anthropogenic causes of climate change
 - Would continue 25+ year long data record
- Earth Radiation Budget Sensor (ERBS)
 - Continuously monitors the Earth's radiation budget to identify subtle long-term shifts related to climate change
 - Would continue 21+ year long data record
- Ocean Altimeter (ALT)

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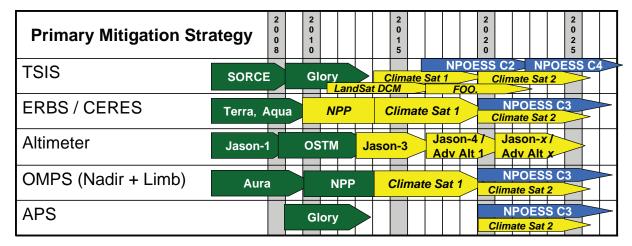
- Monitors sea level
- Would continue 15+ year long data record
- Ozone Mapping and Profiler Suite (OMPS) Limb Subsystem
 - Measures the vertical distribution of stratospheric ozone to monitor and understand the ozone recovery resulting from the Montreal Protocol
 - Would continue 23+ year long data record
- Aerosol Polarimetry Sensor (APS)
 - Measures the global distribution of aerosols and their impact on the Earth's energy balance, clouds, and precipitation
- Conical Scanning Microwave Imager (CMIS) Reduced Capability
 - Provides sea surface temperatures, sea ice and snow cover extents, soil moisture, ocean surface wind speed, water vapor, and precipitation rates even in the presence of heavy cloud cover
 - Continuous records date back to 1987
- Visible Infrared Imaging Radiometer Suite (VIIRS) Reduced Coverage (Absent from 0930 Orbit)
 - Multi-spectral imagers sample the spectral signatures of features on or near the Earth's surface important to climate science
 - For over three decades, scientists have depended on this imagery for a wide variety of weather and climate applications
- Cross-track Infrared Sounder (CrIS)/Advanced Technology Microwave Sounder (ATMS) Reduced Coverage (Absent from 0530 Orbit)
 - No mitigation recommended for climate science
- Space Environment Sensor Suite (SESS)
 - Not considered here

Development of Mitigation Options [p. 5]

- Multiple options exist to mitigate the loss of sensors from NPOESS
- Developed options using following criteria:
 - Minimize risk to measurement continuity
 - First priority for existing climate data records
 - Minimize risk to existing programs
 - Cost effectiveness
 - · Economies of scale
 - Leverage planned missions and sensors including partnerships with other space agencies

Potential Mitigation Options [p. 6]

- Option 1: NPOESS + Gap Filler Climate Satellite
- Option 2: Sequential Climate Satellites
- Option 3: Sequential Climate Satellites w/TSIS Redundancy
- Option 4: Sequential Climate Satellites w/TSIS Redundancy & Operational Risk Reduction
- These options also include free-flyer altimetry missions and climate data record science support



Current and Planned Missions
NASA-NOAA Mitigation Flight
NPOESS Mitigation Flight

FIGURE [C.1] Range of Options Examined for Climate Data Continuity. [p. 7]

WHITE PAPER BASELINE:								
Missions	LRD	TSIS	ERBS / CERES	ALT	OMPS	APS		
OSTM (Jason 2):	2008			Poseidon 3				
Glory:	2009	TIM				APS		
NPP:	2010		CERES		OMPS-Limb			
NPOESS C1 Mission:	2013		ERBS		OMPS-Limb	APS		
NPOESS C2 Mission:	2016	TSIS						
NPOESS C3 Mission:	2020		ERBS		OMPS-Limb	Follow-on APS		
NPOESS C4 Mission:	2022	TSIS						
LDCM Mission:	2011							
Flight of Opportunity:	2017							
Jason 3 Mission:				ALT				
Jason 4 Mission:								
Jason 5 Mission:	_							
Advanced Altimeter Mission # 1:	2017			ADV ALT				
Advanced Altimeter Mission # 2:	2021			ADV ALT				
Climate Free-Flyer # 1:								
Climate Free-Flyer # 2:	2020							
Notes: = Mission in Formulation or Development = Mission Concept to Restore NPOESS De-Manifested Climate Sensors = Mission Not Involved in this Option								

FIGURE [C.2] Initial Recommendation from January 2007 Joint Assessment. [p. 8]

• VIIRS flies on NPP, C1, C2, C3, and C4

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- AVHRR flies on METOP mid-morning orbit
- CMIS to be replaced by MIS starting with C2

Missions	LRD	TSIS	ERBS / CERES	ALT	OMPS	APS	
OSTM (Jason 2):	2008			Poseidon 3			
Glory:	2009	TIM				APS	
NPP:	2010		CERES		OMPS-Limb		
NPOESS C1 Mission:	2013						
NPOESS C2 Mission:	2016	TSIS					
NPOESS C3 Mission:	2020		ERBS		OMPS-Limb	Follow-on APS	
NPOESS C4 Mission:	2022	TSIS					
LDCM Mission:	2011	TSIS					
Flight of Opportunity:	2017						
Jason 3 Mission:	2013			ALT			
Jason 4 Mission:	2017						
Jason 5 Mission:	2021						
Advanced Altimeter Mission # 1:	2017			ADV ALT			
Advanced Altimeter Mission # 2:	2021			ADV ALT		APS	
Climate Free-Flyer # 1:	2014	TSIS	ERBS		OMPS		
Climate Free-Flyer # 2:	2020						
lotes: = Mission in Formulation or Development = Mission Concept to Restore NPOESS De-Manifested Climate Sensors							

FIGURE [C.3] Option 1. NPOESS + Climate Satellite. [p. 9] NOTES:

= Potential addition to option

- The manifest for C1 is frozen based on technical risk considerations
 - VIIRS flies on NPP, C1, C2, C3, and C4
 - AVHRR flies on METOP mid-morning orbit
 - CMIS to be replaced by MIS starting with C2

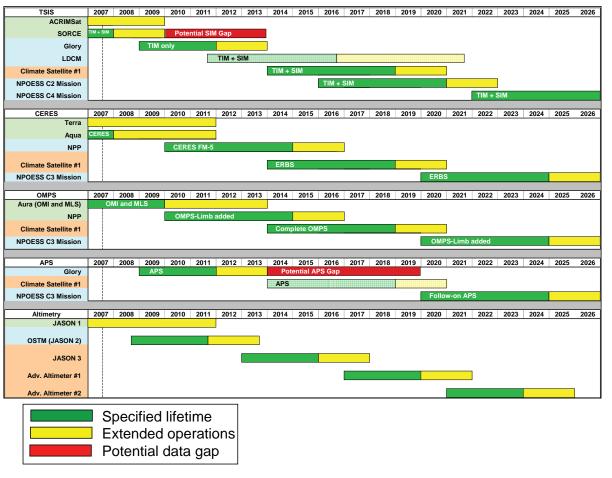


FIGURE [C.4] Option 1. Continuity Timeline. NPOESS + Climate Satellite. [p. 10]

OPTION # 2:								
Missions	LRD	TSIS	ERBS / CERES	ALT	OMPS	APS		
OSTM (Jason 2):	2008			Poseidon 3				
Glory:	2009	TIM				APS		
NPP:	2010		CERES		OMPS-Limb			
NPOESS C1 Mission:	2013							
NPOESS C2 Mission:	2016							
NPOESS C3 Mission:	2020				OMPS-Limb*			
NPOESS C4 Mission:	2022							
LDCM Mission:	2011	TSIS						
Flight of Opportunity:	2017							
Jason 3 Mission:	2013			ALT				
Jason 4 Mission:	2017							
Jason 5 Mission:	2021							
Advanced Altimeter Mission # 1:	2017			ADV ALT				
Advanced Altimeter Mission # 2:	2021			ADV ALT				
Climate Free-Flyer # 1:	2014	TSIS	ERBS		OMPS	APS		
Climate Free-Flyer # 2:	2020	TSIS	ERBS		OMPS*	Follow-on APS		
Notes:								
= Mission in Formulation or Development								
= Mission Concept to Restore NPOESS De-Manifested Climate Sensors								
= Mission Not Involved in this Option								
= Potential addition to option * OMPS flies on either C3 or Climate Sat # 2								

FIGURE [C.5] Option 2. Sequential Climate Satellites. [p. 11] NOTES:

- The manifest for C1 is frozen based on technical risk considerations
 - VIIRS flies on NPP, C1, C2, C3, and C4
 - AVHRR flies on METOP mid-morning orbit
 - CMIS to be replaced by MIS starting with C2



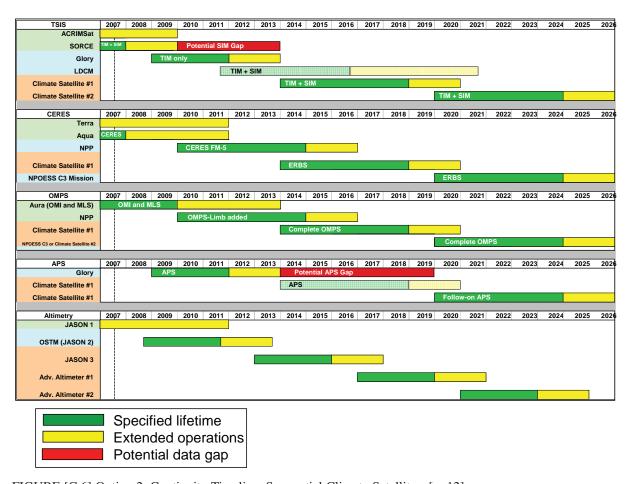


FIGURE [C.6] Option 2. Continuity Timeline. Sequential Climate Satellites. [p. 12]

OPTION # 3:								
Missions	LRD	TSIS	ERBS / CERES	ALT	OMPS	APS		
OSTM (Jason 2):	2008			Poseidon 3				
Glory:	2009	TIM				APS		
NPP:	2010		CERES		OMPS-Limb			
NPOESS C1 Mission:	2013							
NPOESS C2 Mission:	2016							
NPOESS C3 Mission:	2020				OMPS-Limb*			
NPOESS C4 Mission:	2022							
LDCM Mission:	2011	TSIS						
Flight of Opportunity:	2017	TSIS						
Jason 3 Mission:	2013			ALT				
Jason 4 Mission:	2017							
Jason 5 Mission:	2021			ADVALT				
Advanced Altimeter Mission # 1:	2017			ADV ALT				
Advanced Altimeter Mission # 2:	2021	TSIS	EDDC	ADV ALT	OMDC	APS		
Climate Free-Flyer # 1:	2014		ERBS		OMPS			
Climate Free-Flyer # 2:	2020	TSIS	ERBS		OMPS*	Follow-on APS		
Notes:								
= Mission in Formulation or Development								
	= Mission Concept to Restore NPOESS De-Manifested Climate Sensors							
	= Mission Not Involved in this Option							
= Potential addition to option * OMPS flies on either C3 or Climate Sat # 2								
OPTION # 4: Option # 3 with the Climate Free-Flyers having a specified on-orbit life from 5 to 7 years								

FIGURE [C.7] Option 3 and 4. Sequential Climate Satellites + TSIS Redundancy. [p. 13] NOTES:

- The manifest for C1 is frozen based on technical risk considerations
 - VIIRS flies on NPP, C1, C2, C3, and C4
 - AVHRR flies on METOP mid-morning orbit
 - CMIS to be replaced by MIS starting with C2

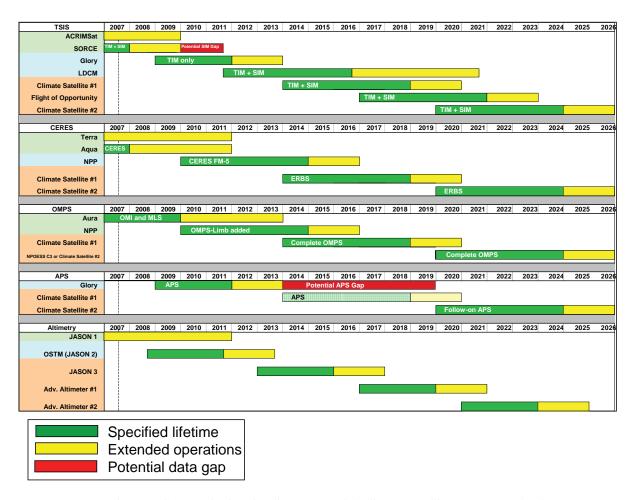


FIGURE [C.8] Option 3 and 4. Continuity Timeline. Sequential Climate Satellites + TSIS Redundancy. [p. 14]

Current Studies [p. 15]

- Work in progress: still exploring options
- NPOESS remanifest
 - Assessed 2 options for earliest return to NPOESS flights (C2-C4)
 - NASA procures and delivers sensors to NPOESS as Government Furnished Equipment (GFE)
 - The Integrated Program Office (IPO) procures sensors via current prime contractor overseeing subcontracted instrument vendors
- Altimetry
 - Altimetry capability explored as free-flying Jason follow-on and as advanced altimeter missions
- Climate satellite missions
 - Examined 2 research-grade missions
 - Additionally explored TSIS (total and spectral) on Landsat Data Continuity Mission (LDCM) and International Space Station (ISS)
 - Currently assessing CERES on NPP

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- Examined 2 operational-grade missions
 - Used sensor analysis from NASA plus spacecraft development analysis from NOAA Polar Extended Mission study (2006)

Climate Data Record (CDR) Science Support [p. 16]

- Includes development, production, reprocessing, stewardship, and distribution
- Assumes data from all NPOESS certified sensors and mitigation sensors/sources
- Covers about 30 Climate Change Science Program essential climate variables
- Will be covered in more detail in following presentation

Free Flyer Climate Satellite [p. 17]

- Would fly in formation with NPOESS PM to provide imager data
- Two options were examined:

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- Research spacecraft
 - Planned 5-year mission
 - Single string development with selective redundancy
 - Inexpensive, non-standard launch vehicle
 - Ground segment leverages existing systems
- Operational spacecraft
 - · Planned 7-year mission with additional redundancy
 - Standard launch vehicle
 - Additional investment in ground segment
- Current cost estimate range for a 3-sensor satellite is approximately \$700M-\$1100M
 - CDR Science Support is an additional \$300M-\$450M

Altimetry Options [p. 18]

- NPOESS sun-synchronous orbits are NOT ideal for precision altimetry
- Flight of an altimeter on NPOESS is NOT recommended
- For this analysis, "free flyer" satellites in the NOAA/EUMETSAT JASON series are assumed
 - Three satellites beyond JASON 2 required to provide coverage to 2026
 - Costs estimated for JASON 3, 4, and 5
 - Advanced altimeter costs also estimated
 - May replace JASON class missions starting with JASON 4
- Independent of this study, U.S. Navy is working with the IPO to develop costs and options to procure an
 operational oceanography radar altimeter
- Current total cost estimate for a series of 3 missions ranges from approximately \$1.5B-\$2.1B
 - CDR Science Support is an additional ~\$200M
 - Current cost estimate for a single JASON follow-on is approximately \$470M with the potential for 50/50 cost sharing with partners

TABLE Climate Goal Partnering Opportunities (Preliminary) [p. 19]

	Partner	Sensor or Capability	Timeframe	Role
	EUMETSAT	Jason-3	2013-2018	Mitigate
	NASA/Navy	Adv. Altimeter	TBD	Mitigate
1	ESA/JAXA (Earthcare)	APS/ERBS-like	2010-20xx	Mitigate
ial	ESA GMES Sentinel 3	Altimeter		Complement
Potential	Navy (NPOESS)	Altimeter (Op)	2016-2026	Complement
Pot	Navy (DoD Space Test Program)	Altimeter (Op)		Complement
	CNES Megha-Tropiques	ERBS-like		Complement
ısir	Chinese SOA (HY series)	Altimeter		Mitigate
Increasing	Brazilian Space Agency (Amazonia)	Flight Opportunity	2010/2015	Accommodation
ľ	EUMETSAT (MSG)	ERBS-like	on-orbit	Complement
. ,	Chinese Met. Agency (FY series)	ERBS-like		Mitigate
	ESA PARASOL	APS-like	on-orbit	Complement

Related Concerns [p. 20]

VIIRS

- Reduced imaging capability for mid-morning orbit
 - · Discussions on-going with EUMETSAT about an advanced imager on METOP-D
- Optical Crosstalk

MIS

- Reduced capability microwave imager
- First MIS scheduled to fly on NPOESS C2 (2016)
- Discussion on-going with JAXA about AMSR-2
- Pursuing several options for continuity of ocean vector wind measurements

TABLE Near-Term Planning [p. 21]

	Decision/Funding Commitment	Launch Readiness Date		
CERES on NPP	September 2007 / FY07*	September 2009		
TSIS on LDCM	January 2008 / FY09	Late 2011		
JASON-3	Decision CY08 / FY10	2013		
First Climate Free-Flyer	Mid 2009 / Pre-Phase A FY08	2014		

^{*} Would require re-allocation of existing funds

Next Steps [p. 22]

- Listen closely to the input from this Workshop
- Continue to work with OSTP
- Continue dialogue regarding potential international and/or domestic partnerships

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Backups [pp. 23-24]

		EARLY-AM		MID-AM			РМ		
NPOESS Instruments	NPP	New C2 (2016)	New C4 (2022)	Old (C3)	Mario	Old (C6) (2016)	New C1 (2013)	New C3 (2020)	
		Old (C2) (2011)	Old (C5) (2015)	(2013)	MetOp		Old (C1) (2009)	Old (C4) (2014)	
Reduced Capability Sensors									
CMIS*		✓	>					√	
Reduced Coverage Sensors									
CrIS/ATMS	/				✓ IASI/AMS		✓	✓	
VIIRS	/	✓	~		✓ AVHRR		✓	√	
De-manifested Sensors									
TSIS									
CERES/ERBS							CERES		
ALT									
OMPS**	✓						✓	√	
APS									
Remains Intact No Change/Not Relevant *CMIS to be redefined as a less capable, less expensive sensor **OMPS Limb Subsystem is cancelled and only the Nadir capability is maintained									

FIGURE [C.9] NPOESS Nunn-McCurdy Certification. Reductions of Climate-Relevant Sensors. [p. 24]

Appendix D

Abbreviations and Acronyms

(A)ATSR Advanced Along-Track Scanning Radiometer (also AATSR)

ABI Advanced Baseline Imager

ACE aerosol-cloud-ecosystem (mission)

ACRIMSAT Active Cavity Radiometer Irradiance Monitor Satellite

ADCS Altitude Determination and Control System

ADM Air Data Management
AIRS Atmospheric Infrared Sounder
ALOS Advanced Land Observation Satellite

ALT altimeter

AMSR-E Advanced Microwave Scanning Radiometer for the Earth Observing System

AMSU Advanced Microwave Sounding Unit

AoA Analysis of Alternatives
APS Aerosol Polarimeter Sensor
ASAR Advanced Synthetic Aperture Radar

ASCAT advanced scatterometer

ASCENDS Active Sensing of CO₂ Emissions over Nights, Days, and Seasons ASTER Advanced Spacebone Thermal Emission and Reflection Radiometer

ATLID Atmospheric Light Detection and Ranging Instrument

ATMS Advanced Technology Microwave Sounder AVHRR Advanced Very High Resolution Radiometer

BIOMASS Biomass monitoring mission for carbon assessment (ESA)

CALIPSO Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations

CDR climate data record

CEOS Committee on Earth Observations Satellites
CERES Clouds and Earth's Radiant Energy System

CERES S'COOL Clouds and Earth's Radiant Energy System Students' Clouds Observations On-Line

CGMS Coordination Group for Meteorological Satellites

CHAMP Coral Health and Monitoring Project or Challenging Minisatellite Payload

CLARREO Climate Absolute Radiance and Refractivity Observatory

CMIS Conical Microwave Imager and Sounder

CNES Centre National d'Etude Spatiales

COSMIC Constellation Observing System for Meteorology, Ionosphere, and Climate

CrIS Cross-track Infrared Sounder CryoSat Cryosphere Satellite (mission)

DESDynI Deformation, Ecosystem Structure, and Dynamics of Ice Mission

DMSP Defense Meteorological Satellite Program

DOD Department of Defense

DSCOVR Deep Space Climate Observatory

EarthCARE ESA's cloud and aerosol (mission)

ECMWF European Centre for Medium-Range Weather Forecasts

ECV essential climate variable
EDR environmental data record
ENVISAT Environmental Satellite
EOS Earth Observing System
ERB Earth's radiation budget
ERBS Earth Radiation Budget Sensor

ESA European Space Agency

ET-EGOS Expert Team on Evolution of the Global Observing System

EUMETSAT European Organization for the Exploitation of Meteorological Satellites

Feng Yun Feng Yun Wind and Cloud (meteorological satellite)
FPAR fraction of photosynthetically active radiation

GACM Global Atmospheric Composition Mission GCOM Global Change Observation Mission GCOS Global Climate Observing System

GEMS Global and regional Earth-system (Atmosphere) Monitoring

GEO geosynchronous Earth orbit

GEOSS Global Earth Observation System of Systems

GERB geostationary Earth radiation budget
GFO Geosat (Geodetic Satellite) Follow-on
GHRSST-PP Global High Resolution SST Pilot Project

GIFTS Geosynchronous Imaging Fourier Transform Spectrometer

GLAS Geoscience Laser Altimeter System

GLI Global Imager

GLM Geostationary Lightning Mapper

GMES Global Monitoring for Environmental Security

GMI Giant Magneto-Impedance

GMS Geostationary Meteorological Satellite

GOES Geostationary Operational Environmental Satellite

GOME Global Ozone Monitoring Experiment

GOS Global Observing System

GOSAT Greenhouse Gases Observing Satellite
GPM Global Precipitation Measurement

GPS/RO Global Positioning System/Radio Occultation

GRACE Gravity Recovery and Climate Experiment

GRAS Global Navigation Satellite System Receiver for Atmospheric Sounding

HES Hyperspectral Environmental Suite
HIRDLS High-Resolution Dynamics Limb Sounder
HIRS High-Resolution Infrared Radiation Sounder

IASI Infrared Atmospheric Sounding Interferometer ICESat Ice, Cloud, and Land Elevation Satellite IEOS Integrated Earth Observation System

IOCCG International Ocean Colour Coordination Group

IORD Integrated Operational Requirements Document (NPOESS)

IOS Integrated Observing System

IPCC Intergovernmental Panel on Climate Change

IR infrared

IRS Indian Remote Sensing Satellite

ISRO Indian Space Agency

ITAR International Traffic in Arms Regulations ITSC Information Technology Support Center

JAXA Japan Aerospace Exploration Agency

LAI leaf area index

LDCM Landsat Data Continuity Mission

LEO low Earth orbit

MAM mirror attenuated mosaic

MERIS Medium Resolution Imaging Spectrometer (ESA)

Meteorological satellite for European counterpart to GOES

MetOp Meteorological Operational Satellite (European)

METSAT Meteorological Satellite

MIPAS Michelson Interferometer for Passive Atmospheric Sounding

MIS Microwave Imager and Sounder

MISR Multi-angle Imaging Spectro-Radiometer

MLS microwave limb sounder

MODIS Moderate Resolution Imaging Spectro-Radiometer

MSG Meteosat Second Generation MSU microwave sounding unit

NASA National Aeronautics and Space Administration

NESDIS National Environmental Satellite Data and Information Service

NESDIS/STAR National Environmental Satellite Data and Information Service/Center for Satellite

Applications and Research

NIR near infrared

NIST National Institute of Standards and Technology NOAA National Oceanic and Atmospheric Administration

NODC National Oceanic Data Center (NOAA)

NPOESS National Polar-orbiting Operational Environmental Satellite System

NPP NPOESS Preparatory Project NRC National Research Council

NSTC National Science and Technology Council

OCO Orbiting Carbon Observatory
OLS Operational Line Scanner
OMI Ozone Monitoring Instrument
OMPS Ozone Mapping and Profiler Suite
OPAG Open Programme Area Group

OSIP Operational Satellite Improvement Program
OSSE Observing System Simulation Experiment
OSTM Ocean Surface Topography Mission
OSTP Office of Science and Technology Policy
OSTST Ocean Surface Topography Science Team

P³I preplanned product improvement

PALSAR Phased Array type L-band Synthetic Aperture Radar

PARASOL Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with

Observations from a Lidar

PATH Precipitation and All-Weather Temperature and Humidity
POES Polar-orbiting Operational Environmental Satellite
POLDER Polarization and Directionality of Earth's Reflectances

QuikSCAT Quick Scatterometer

RADARSAT Radar Satellite (Canada)

SAGE Stratospheric Aerosol and Gas Experiment

SAR synthetic aperture radar SARAL Satellite with Argos and AltiKa

SARSAT Search and Rescue Satellite Aided Tracking SBUV Solar Backscatter Ultraviolet Instrument

SBUV/2 Solar Backscatter Ultraviolet Spectral Radiometer, MOD 2

ScaRAB Scanner for the Radiation Budget

SCIAMACHY Scanning Imaging Absorption Spectrometer for Atmospheric Chartography

SCLPSnow and Cold Land ProcessesSeaWiFSSea-Viewing Wide-Field SensorSESSSpace Environment Sensor Suite

SEVIRI Spinning Enhanced Visible and Infrared Imager

SGLI Second Generation Global Imager SIM Spectral Irradiance Monitor

SMAP Software Assurance Management Program

SMMR Scanning Multichannel (or Multifrequency) Microwave Radiometer

SMOS Soil Moisture and Ocean Salinity
SOHO Solar and Heliospheric Observatory
SORCE Solar Radiation and Climate Experiment
SPOT Satellite Probatoire de l'Observation de la Terre

SSI spectral solar irradiance

SSM/I Special Sensor Microwave Imager

SSMIS Special Sensor Microwave Imager/Sounder

SST sea surface temperature

STAR Center for Satellite Applications and Research

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SuS Survivability Sensor

SWOT Surface Water-Ocean Topography

TES Tropospheric Emission Spectrometer

TIM Total Irradiance Monitor

TMI TRMM [Tropical Rainfall Measuring Mission] Microwave Imager

TOMS Total Ozone Mapping (Spectrolab/System/Spectrometer)

TOPEX Ocean Topography Experiment
TRMM Tropical Rainfall Measuring Mission

TSI total solar irradiance
TSIS Total Solar Irradiance Suite

UARS Upper Atmosphere Research Satellite
UNEP United Nations Environment Programme

UNESCO United Nations Educational, Scientific and Cultural Organization

UV ultraviolet

VAS VISSR Atmospheric Sounder

VIIRS Visible/Infrared Imager/Radiometer Suite

VIRI visible and infrared imager

VISSR Visible and Infrared Spin Scan Radiometer

WindSat a joint Integrated Program Office/DOD/NASA satellite-based polarimetric microwave

radiometer

WMO World Meteorological Organization

XOVWM Extended Ocean Vector Winds Mission

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Appendix E

Biographical Sketches of Panel Members

ANTONIO J. BUSALACCHI, JR., *Chair*, is director of the Earth System Science Interdisciplinary Center and a professor in the Department of Atmospheric and Oceanic Science at the University of Maryland. His research interests include tropical ocean circulation and its role in the coupled climate system, and climate variability and predictability. Dr. Busalacchi has been involved in the activities of the World Climate Research Program (WCRP) for many years as co-chair of the scientific steering group for its subprogram on climate variability and predictability, and he currently is a member of the Joint Scientific Committee of the WCRP. Dr. Busalacchi has extensive NRC experience as a member of the Climate Research Committee, the Committee on Earth Studies, the Panel on the Tropical Ocean Global Atmosphere Program, and the Panel on Ocean Atmosphere Observations Supporting Short-Term Climate Predictions.

PHILIP E. ARDANUY is chief scientist and director of Remote Sensing Applications at Raytheon Information Solutions. Dr. Ardanuy specializes in developing integrated mission concepts through government-industry-academic partnerships. His research has included network-centric and system-of-systems concepts, telepresence-telescience-telerobotics, tropical meteorology, Earth's radiation budget and climate, satellite instrument calibration and characterization, remote sensing applications and systems engineering, scientific applications research-to-operational transition, and validation of environmental observations. He is the associate editor of the International Society for Optical Engineering's (SPIE) *Journal of Applied Remote Sensing* and chair of the American Meteorological Society's (AMS) Committee on Satellite Meteorology and Oceanography. Dr. Ardanuy has received multiple honors, including his 2007 elevation to the position of Raytheon Engineering Fellow and his receipt of the Raytheon Excellence in Business Development Award and the Raytheon Peer Award for "dedication in the excellence in his work and unimagined expertise in algorithms, ground processing, mission understanding, and mission experience." Dr. Ardanuy served on the NRC Panel on Earth Science Applications and Societal Benefits of the Committee for Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, and on the Committee on Utilization of Environmental Satellite Data: A Vision for 2010 and Beyond.

JUDITH A. CURRY is chair of the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. Her research interests include remote sensing, climate of the polar regions, atmospheric modeling, and air/sea interactions. She participates in the World Meteorological Organization's World Climate Research Program, was a member of the Science Steering Group of the Arctic Climate System Program, and chairs the Global Energy

and Water Cycle Experiment Cloud System Studies Working Group on Polar Clouds. She co-chaired the Surface Heat Budget of the Arctic Ocean program's Science Working Group. Dr. Curry previously served on the NRC Committee to Review NASA's Polar Geophysical Data Sets, the Panel on Coastal Meteorology, and the Climate Research Committee. She currently serves on the Space Studies Board.

JUDITH L. LEAN has worked in the Naval Research Laboratory's Space Science Division since 1986, where her research focuses on the mechanisms, measurements, and modeling of variations in the Sun's radiative output and the effects of this variability on Earth's global climate and space weather. She is a guest investigator on NASA's Upper Atmosphere Research Satellite and the Living with a Star and Sun-Earth Connection programs. She is a coinvestigator on the Solar Radiation and Climate, Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics, and Solar Dynamics Explorer space missions. Dr. Lean has testified before the U.S. Senate Committee on Energy and Natural Resources and the U.S. Senate Committee on Commerce, Science and Transportation Subcommittee on Science, Technology and Space on the science of climate change. She is a fellow of the American Geophysical Union and a member of the International Association of Geomagnetism and Aeronomy, the American Astronomical Society-Solar Physics Division, and the American Meteorological Society. Dr. Lean served on the NRC Committee on Radiative Forcing Effects on Climate, the Board on Atmospheric Sciences and Climate, and the Panel on Climate Variability and Change of the Committee for Earth Science and Applications from Space: A Community Assessment and Strategy for the Future.

BERRIEN MOORE III is a professor of systems research at University of New Hampshire (UNH) and is executive director of Climate Central, Inc. He was director of UNH's Institute for the Study of Earth, Oceans, and Space from 1987 to early 2008. He stepped down as director of the Institute to direct Climate Central. 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. At UNH, he received the university's 1993 Excellence in Research Award and was named University Distinguished Professor in 1997. In 2005, he was honored with National Oceanic and Atmospheric Administration (NOAA) Administrator's Special Recognition award for his service as chair of the NOAA Research Review Team. Dr. Moore was the recipient of the 2007 Dryden Lectureship in Research by the American Institute of Aeronautics and Astronautics (AIAA). Most recently, he shared in the 2007 Nobel Peace Prize awarded to the Intergovernmental Panel on Climate Change (IPCC); Dr. Moore was the coordinating lead author for the final chapter, "Advancing our Understanding," of the IPCC's Third Assessment Report (2001). He has served on 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 the IGBP. He chaired the 2001 Open Science Conference on Global Change in Amsterdam and is one of the four architects of the Amsterdam Declaration on Global Change. Dr. Moore has contributed actively to committees at the NRC, and he served as vice chair of the NRC Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future. He is chair of the Committee on Earth Studies and is a member of the Space Studies Board.

JAY S. PEARLMAN is chief engineer of Network Centric Operations (NCO) Programs and Technologies at the Boeing Company. Dr. Pearlman's background includes basic research program management and program development in sensors, remote sensing, and information systems. He was Boeing's chief architect for the NOAA GOES-R study contract and the chief scientist for the Landsat Data Continuity contract. He was also deputy principal investigator for the NASA Hyperion Program. Dr. Pearlman is currently leading the NCO research and technology coordination and is a Boeing technical fellow. He is a senior member of the IEEE and is chair of the IEEE Committee on Earth Observation. He is active in promoting systems-of-systems architecture and information system development for large-scale national and global applications, including advancing ocean and coastal information systems. Dr. Pearlman has more than 70 publications and 25 U.S. and international patents. He served on the NRC Panel on Enabling Concepts and Technologies of the Committee for the Review of NASA's Pioneering

Revolutionary Technology Program and on the Steering Committee, Space Applications and Commercialization. He is currently a member of the Ocean Studies Board.

JAMES F.W. PURDOM is a senior research scientist at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. Before joining CIRA in 2001, he spent 4 years as director of the Office of Research and Applications in NOAA-NESDIS. Dr. Purdom's research focuses on remote sensing of Earth and its environment from space, as well as the development and evolution of atmospheric convection, with emphasis on the study of mesoscale processes using satellite data. He received the U.S. Department of Commerce Silver Medal in 1994, the National Weather Association Special Award in 1996, the American Meteorological Society Special Award in 1997, and the Presidential Rank Award in 2001. He served on the NRC Task Group on the Availability and Usefulness of NASA's Space Mission Data.

CHRISTOPHER S. VELDEN is currently a research scientist at the University of Wisconsin. He heads a small group that develops satellite products mainly for tropical cyclone applications. He served as a member of the U.S. Weather Research Project Science Steering Committee (1996-1999), the GOES Science Team (1996-1998), and the Geostationary Microwave Sounder Working Group (1995-1996). He served as chair of the AMS Committee on Satellite Meteorology and has also been a member of the AMS Tropical Committee. In the last 5 years he has been honored by AMS with two awards, and he has published numerous papers. He served on the NRC Committee on NOAA-NESDIS Transition from Research to Operations, the Committee on the Future of the Tropical Rainfall Measuring Mission, and the Panel on Weather of the Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future.

THOMAS H. VONDER HAAR is the director of the Cooperative Institute for Research in the Atmosphere and University Distinguished Professor of Atmospheric Science at Colorado State University. His research includes work on Earth's radiation budget and fundamental relationships with the climate system and incorporates some of the first results of direct solar irradiance measurements from satellites and the exchange of energy between Earth and space. Dr. Vonder Haar is also director of the Center for Geosciences, a Department of Defense-sponsored research center that focuses on the study of weather patterns and how they affect military operations, and includes investigations of fog, cloud layering, cloud drift winds, and dynamics of cloud persistence as detected from satellites. He currently serves on the NRC Board on Atmospheric Sciences and Climate and was the vice chair of the Panel on Weather of the Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future. He was elected to the National Academy of Engineering in 2003.

FRANK J. WENTZ serves as director of Remote Sensing Systems, a research company specializing in satellite microwave remote sensing of Earth. His research focuses on radiative transfer models that relate satellite observations to geophysical parameters, with the objective of providing reliable geophysical data sets to the Earth science community. He is currently working on satellite-derived decadal time series of atmospheric moisture and temperature, the measurement of sea surface temperature through clouds, and advanced microwave sensor designs for climatological studies. He is a member of the American Geophysical Union. Mr. Wentz served on the NRC Panel on Reconciling Temperature Observations of the Climate Research Committee, and he was a member of the Committee on Earth Studies.

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Community Letter to NASA and NOAA Regarding Concerns Over NPOESS Preparatory Project VIIRS Sensor and Response by S. Alan Stern

COMMUNITY LETTER

October 2, 2007

Dear Dr. Griffin and Admiral Lautenbacher,

We are ocean biologists and biogeochemists who use NASA satellite data to study the ocean's biosphere, its changes in time, and how it is affected by and responds to humankind's activities. Our science requires satellite "ocean color" sensors that can quantify trends in global ocean biological and biogeochemical properties on intraseasonal to decadal time scales. Ocean color data are critical to address strategic needs of other federal agencies, including the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), and the U.S. Navy. High quality ocean color observations have applications such as detecting and monitoring changes in water quality, tracking harmful algal blooms, assessing underwater visibility for divers, and a variety of other applications related to ocean ecosystems, carbon and elemental cycling, coastal habitats, and coastal hazards. For the past decade, we have been privileged to use the internationally recognized highest quality NASA data sets from SeaWiFS and MODIS on Aqua. These NASA data sets have literally revolutionized our field and greatly enhanced our abilities to inform policymakers and the public of the changes to our oceans.

We have become increasingly concerned that VIIRS (Visible Infrared Imager/Radiometer Suite), the ocean color sensor on the NPOESS Preparatory Project (NPP) mission, will be incapable of providing imagery for climate science applications. VIIRS on NPP was supposed to be the next ocean color mission to follow SeaWiFS and MODIS on Aqua and extend key biological and biogeochemical oceanographic observations. Importantly, this requirement of continuing the EOS-level climate science observations across all Earth Science disciplines was built into the recommendations of the NRC's Decadal Survey committee.

Recent summaries of VIIRS performance from the IPO and NASA, presented at the NPP Science Team Meeting in August 2007, clearly show that the present configuration of the VIIRS sensor will not come close to meeting the VIIRS design specifications and required spectral radiometric accuracies—which are minimum standards for ocean color sensor performance for climate science applications. The so-called "cherry-picked" configuration of the VIIRS's filter array will just meet these standards but only if the rest of pre-flight testing is completely error free (which is unrealistic as VIIRS just entered its testing phase). Hence, we have little confidence that VIIRS on NPP will ever provide well-calibrated ocean color imagery. It may be able to provide qualitative imagery for descriptive purposes (detecting turbid water plumes, etc.), but not the high-quality ocean color imagery required for quantifying the variability and impacts of natural and human-induced changes of our oceans.

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We face the ominous likelihood that in the near future there will be a disruption in climate-quality ocean color data as both MODIS Aqua and SeaWiFS are beyond their designed mission lifetimes. Unfortunately, there is nothing in the first round of Earth Science Decadal Survey plans for EOS-level climate sensors beyond VIIRS on NPP (and then VIIRS on NPOESS). The Decadal Survey recommends a 2013-2016 launch date for the Aerosol/Cloud/Ecosystems (ACE) mission—a mission that if structured properly could significantly contribute to our community. Our understanding, however, is that even a 2016 launch for ACE is optimistic and would require funding for mission planning to begin no later than 2009. As it looks now, both MODIS-Aqua and SeaWiFS sensors are likely to be dead long before the ACE mission's launch.

In contrast to other international partnerships, such as with altimetry, we are not getting much help with global ocean color measurements from our international partners. Unfortunately, present ocean color missions are limited at best. For example, the European Space Agency's (ESA) MERIS mission has a narrow swath (only a third of SeaWiFS's) and has several image quality issues (radiometric inconsistencies, scan line dependence in derived products, no vicarious calibration procedure in place, etc.). We are not able to routinely receive global MERIS Level 1 data nor do we have detailed pre-flight characterization data, so there is no existing way for us to work with ESA to fix these problems. Nearly all other international ocean color missions in space today lack global coverage and are experimental imagers with narrow swaths and poorly characterized imaging capabilities. Again, data access remains difficult and we have little ability to understand their capabilities. Future international missions are likewise problematic, as launch dates are far into the future, and we anticipate the same problems we have today with current international sensors (limited access to data, poor sensor characterization, etc.).

We see three choices that the Space and Earth science agencies can make; each has serious and long-term consequences for our scientific discipline, the management of ocean resources, and society's ability to understand climate change and mitigate human impacts on ocean habitats and ecosystems. These are:

- 1. Aggressively pursue and document improvements to the VIIRS sensor on NPP that enable it to meet the specifications required for climate capable ocean color observatories,
- 2. Implement a stand-alone, global ocean color mission, or
- 3. Continue with plans of flying NPP, but in full recognition of its consequences.
- 1. An aggressive rehabilitation of VIIRS on NPP is theoretically possible, and scientists and engineers at NASA GSFC have long been considering it. As you likely know, there are many issues (institutional, contractual, fiscal, schedule, interagency agendas, etc.) that will make the successful rehabilitation of VIIRS extremely difficult. This strategy will require a much improved and transparent pre-launch testing and on-orbit calibration/validation program (including on-orbit maneuvers for lunar calibrations) than is in place today for the NPP program. Even if this plan were to be pursued, there is no certainty that it will work in the end. For example, the MODIS sensor on the Terra platform has yet to provide stable ocean color data products despite many person years of effort. MODIS on Terra has shown substantial radiometric signal degradation on orbit (up to 40%). This degradation varies with scan angle and mirror-side and may have resulted from damage done to the mirror coatings in pre-launch testing after its pre-launch characterization. Limitations with the on-orbit calibration system (e.g., solar diffuser door anomaly, inability to track polarization changes) have resulted in temporal variations in calibrated radiances that obfuscate ocean color trends. Seven years after its launch, researchers at the Goddard Space Flight Center (GSFC) are still working to produce high-quality, ocean color data products from MODIS on Terra.
- 2. A gap-filling mission in the spirit of SeaWiFS can be implemented and flown. SeaWiFS is a success story of the "better, faster, cheaper" version of NASA. A dedicated, single-instrument ocean mission can be flown easily and cost-effectively. NASA has launched "quick recovery" missions before. The Quick Scatterometer (QuikSCAT) mission was launched to fill the critical data gap created after the NASA Scatterometer (NSCAT) failed. The ocean color science community has learned much over the last decade about what is required for a successful mission. NASA HQ has requested a detailed concept study for this type of mission and this work is being conducted at the Goddard Space Flight Center. This gap-filling sensor could also be placed on a mission of opportunity. This is clearly the lowest-risk option for insuring that high-quality ocean color data are available for the next decade of science and applications.
- 3. The last choice is the situation we find ourselves in today, and arguably the worst-case scenario. Staying the course with NPP will clearly not result in climate-quality ocean color data. This decision must be made with the understanding that these data will not be available at the time when efforts to address climate change, coastal hypoxia, harmful algal blooms, fisheries health, ocean acidification, and many other issues are accelerating. The bottom line

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is that essential research-quality ocean color data will not be available in the very near future unless immediate and substantive actions are taken. The lack of global ocean color observations at the accuracy and quality of which NASA is currently capable will impact critical climate research conducted in the U.S. Ocean Carbon and Biogeochemistry (OCB) program as well as ocean observatory efforts currently coming on-line from the National Science Foundation (OOI) and NOAA (IOOS). In particular, there will be no way to integrate the invaluable in situ regional observations of the ocean observatory nodes with global observations of ocean plants, animals, and overall health and chemistry for better understanding and prediction of Earth System responses to climate variability and change. Without global and high-resolution coastal ocean color data, there will unquestionably be an impact on implementation and delivery of results to support goals of the Climate Change Science Program (e.g., carbon cycle and ecosystem science), the U.S. Ocean Action Plan and recently released Ocean Research Priorities Plan themes, and the Global Earth Observation System of Systems objectives.

We thank you for your attention and consideration of this matter. Please let us know what we can do to help.

Sincerely,

David A. Siegel, Professor of Marine Science and Director of the Institute for Computational Earth System Science, University of California, Santa Barbara, and member of the NASA NPP Science Team

James Yoder, Senior Scientist, Woods Hole Oceanographic Institution; former Chair of the Carbon Cycle Scientific Steering Group, current Chair of the International Ocean Color Coordinating Group, and former member of ESSAAC

[Also included in the letter were 56 supporting signatures; they are not shown here.]

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RESPONSE

National Aeronautics and Space Administration

Headquarters

Washington, DC 20546-0001



NOV 2 0 2007

Reply to Attn of

SMD/Earth Science Division

Drs. Siegel and Yoder University of California Santa Barbara, California 93106

Dear Drs. Siegel and Yoder:

Thank you for the letter of October 2, 2007. The letter clearly stated community concerns regarding the status of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) Visible/Infrared Imager/Radiometer Suite (VIIRS) for ocean color data. NASA values the scientific information and perspectives provided by the scientific community, and I thank you for offering your views regarding the future of ocean color remote sensing.

On October 5, 2007, the NPOESS Executive Committee (EXCOM) met and decided to remain with the baseline filter for VIIRS given the replacement risks and lack of clear path to improved performance. The Integrated Program Office (IPO) will continue to pursue all other options (including the cherry-picked filter characterization, the remanufactured integrated filter assembly (IFA), and the new design IFA) to improve Color Imagery (CI) performance. In the event of major schedule disruption to the NPP unit as result of other problems, the EXCOM would reconsider the NPP IFA status.

NASA recognizes the well-founded concerns of the community. Ocean color is an important data record for climate science, and we acknowledge that the anticipated performance of VIIRS on NPP puts that record at risk and wish to remedy this situation. We are doing our best within existing constraints to continue the time series of key climate observations (from the Earth Observing System era) on which NASA depends for its mission in Earth System Science. We will continue to work within the U.S. Government to identify acceptable solutions to this problem and encourage community involvement in that process. We look forward to continuing this dialogue.

Sincerely,

S. Alan Stern

Associate Administrator for Science Mission Directorate

D

Acronyms

ABI Advanced Baseline Imager
ABS Advanced Baseline Sounder

ACRIM Active Cavity Radiometer Irradiance Monitor

ADCS Advanced Data Collection System
ADM Atmospheric Dynamics Mission
AIRS Atmospheric Infrared Sounder

ALT altimeter

AMS American Meteorological Society

AMSR-E Advanced Microwave Scanning Radiometer for the Earth Observing System

AMSU Advanced Microwave Sounding Unit

APS Aerosol Polarimeter Sensor

APU accuracy, precision, and uncertainty
ATMS Advanced Technology Microwave Sounder

ATOVS Advanced TIROS Operational Vertical Sounder AVHRR Advanced Very High Resolution Radiometer

CCSP Climate Change Science Program

CDR climate data record

CEOS Committee on Earth Observation Satellites
CERES Clouds and Earth's Radiant Energy System
CGMS Coordination Group for Meteorological Satellites

CIMSS Cooperative Institute for Meteorological Satellite Studies CLARREO Climate Absolute Radiance and Refractivity Observatory

CMIS Conical Microwave Imager and Sounder CNES Centre National d'Etudes Spatiales CNSA China National Space Administration

COCTS Chinese Ocean Color and Temperature Scanner CONAE Comision Nacional de Actividades Espaciales

CRE cloud radiative effect

CrIS Cross-track Infrared Sounder
CryoSat-2 Cryosphere Satellite 2
CWI Coastal Waters Imager
CZCS Coastal Zone Color Scanner
CZL Coastal Zone Imager

CZI Coastal Zone Imager

DAAC Distributed Active Archive Center

DMSP Defense Meteorological Satellite Program

DOD Department of Defense

DORIS Doppler Orbitography and Radiopositioning Integrated by Satellite

ECCO Estimating the Circulation and Climate of the Ocean

ECV essential climate variable
EDR environmental data record
ENSO El Niño/Southern Oscillation
EOS Earth Observing System/Satellite

ERB Earth radiation budget

ERBE Earth Radiation Budget Experiment
ERBS Earth Radiation Budget Sensor
ESA European Space Administration
ESSP Earth System Science Pathfinder

EUMETSAT European Organization for the Exploitation of Meteorological Satellites

FAA Federal Aviation Administration

FM flight model

GCOM Global Change Observation Mission

GCM global climate model

GCOS Global Climate Observing System

GEO geostationary Earth orbit GEO Group on Earth Observations

GEO-CAPE Geostationary Coastal and Air Pollution Events
GEOSS Global Earth Observation System of Systems
GEWEX Global Energy and Water Cycle Experiment
GMES Global Monitoring for Environment and Security

GMI GPM Microwave Imager

GOCE Gravity field and steady-state Ocean Circulation Explorer

GOES Geostationary Operational Environmental Satellite

GOME-2 Global Ozone Monitoring Experiment-2

GPM Global Precipitation Mission GPS Global Positioning System

GRACE Gravity Recovery and Climate Experiment

HAB harmful algal bloom

HES Hyperspectral Environmental Suite

HIRS High-Resolution Infrared Radiation Sounder

IASI Infrared Atmospheric Sounding Interferometer

IDPS Integrated Data Processing System
IEOS Integrated Earth Observation System

IFA integrated filter assembly

IJPS Initial Joint Polar-orbiting Satellite system **IOOS** Integrated Ocean Observing System

IORD Integrated Operational Requirements Document (NPOESS)

IPCC Intergovernmental Panel on Climate Change

IPO Integrated Program Office

IR infrared

ISRO Indian Space Research Organisation **ITAR** International Traffic in Arms Regulations

JAXA Japan Aerospace Exploration Agency

JPS Joint Polar System

KPP key performance parameter

LDCM Landsat Data Continuity Mission

LEO low Earth orbit LT local time LW longwave

MERIS Medium Resolution Imaging Spectrometer MetOp Meteorological Operational Satellite (European)

MIS Microwave Infrared and Sounder **MISR** Multi-angle Imaging SpectroRadiometer

MMRS Multispectral Medium Resolution Scanner **MODIS** Moderate Resolution Imaging Spectroradiometer

MSU Microwave Sounding Unit Meteosat Third Generation **MTG**

MW microwave

NAO North Atlantic Oscillation

NASA National Aeronautics and Space Administration **NDVI** Normalized Difference Vegetation Index

NESDIS National Environmental Satellite Data and Information Service

NIR near infrared

NIST National Institute of Standards and Technology National Oceanic and Atmospheric Administration **NOAA**

NPOESS National Polar-orbiting Operational Environmental Satellite System

NPP NPOESS Preparatory Project NRC National Research Council **NRL** Naval Research Laboratory

NSTC National Science and Technology Council

NWA National Weather Association **NWP** Numerical Weather Prediction **NWS** National Weather Service

OCM Ocean Colour Monitor

OGCM Ocean General Circulation Model **OLR** outgoing longwave radiation **OLS** Operational Linescan System

OMI Ozone Monitoring Instrument
OMPS Ozone Mapping and Profiler Suite

OSSE Observing System Simulation Experiment
OSIP Operational Satellite Improvement Program

OSTM Ocean Surface Topography Mission
OSTP Office of Science and Technology Policy

PDO Pacific Decadal Oscillation

POES Polar-orbiting Operational Environmental Satellites
POLDER Polarization and Directionality of the Earth's Reflectances

SAGE Stratospheric Aerosol and Gas Experiment SARSAT Search and Rescue Satellite Aided Tracking

SBUV/2 Solar Backscatter Ultraviolet Spectral Radiometer, MOD 2

SeaWiFS Sea-viewing Wide Field-of-view Sensor

SEM Space Environment Monitor
SESS Space Environment Sensors
SI Le Système International d'Unités
SIM Spectral Irradiance Monitor
SLR satellite laser ranging

SMM Solar Maximum Mission

SMMR Scanning Multi-channel Microwave Radiometer

SMOS soil moisture and ocean salinity
SODA simple ocean data assimilation
SOHO Solar and Heliospheric Observatory
SORCE Solar Radiation and Climate Experiment
SSM/I Special Sensor Microwave Imager

SST sea-surface temperature

STAR Center for Satellite Applications and Research

SUAG Science User Advisory Group

SVW surface vector winds

SW shortwave

SWIR shortwave infrared

TIM Total Irradiance Monitor TOA top of atmosphere

TOMS Total Ozone Mapping Spectrometer TOPEX Ocean Topography Experiment

T/P TOPEX/Poseidon

TRMM Tropical Rainfall Measuring Mission

TSI total solar irradiance
TSIS Total Solar Irradiance Suite

UARS Upper Atmosphere Research Satellite

UV ultraviolet

VAS VISSR Atmospheric Sounder

VIIRS Visible/Infrared Imager/Radiometer Suite

VIRGO Variability of solar Irradiance and Gravity Oscillations

VIS visible

WCRP World Climate Research Programme
WMO World Meteorological Organization
WOCE World Ocean Circulation Experiment

XBT expendable bathythermograph

XOVWM Extended Ocean Vector Winds Mission

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Committee and Staff Biographical Information

ANTONIO J. BUSALACCHI, JR., *Chair*, is the director of the Earth System Science Interdisciplinary Center and a professor in the Department of Atmospheric and Oceanic Science at the University of Maryland. His research interests include tropical ocean circulation and its role in the coupled climate system and climate variability and predictability. Dr. Busalacchi has been involved in the activities of the World Climate Research Program for many years and currently is co-chair of the scientific steering group for its subprogram on climate variability and predictability. Dr. Busalacchi has extensive NRC experience, including serving on the Climate Research Committee and its associated Panel on the Tropical Ocean Global Atmosphere Program, as well as the Committee on Earth Studies. He chaired the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

PHILIP E. ARDANUY is chief scientist and director of Remote Sensing Applications at Raytheon Information Solutions. Dr. Ardanuy specializes in developing integrated mission concepts through government-industry-academic partnerships. His research has included network-centric and system-of-systems concepts, telepresence-telescience-telerobotics, tropical meteorology, Earth's radiation budget and climate, satellite instrument calibration and characterization, remote sensing applications and systems engineering, scientific applications research-to-operational transition, and validation of environmental observations. He is the associate editor of the International Society for Optical Engineering's (SPIE) *Journal of Applied Remote Sensing* and chair of the American Meteorological Society's (AMS) Committee on Satellite Meteorology and Oceanography. Dr. Ardanuy has received multiple honors, including his 2007 elevation to the position of Raytheon Engineering Fellow and his receipt of the Raytheon Excellence in Business Development Award and the Raytheon Peer Award for "dedication in the excellence in his work and unimagined expertise in algorithms, ground processing, mission understanding, and mission experience." Dr. Ardanuy served on the NRC Panel on Earth Science Applications and Societal Benefits of the Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, and on the Committee on Utilization of Environmental Satellite Data: A Vision for 2010 and Beyond. He was a member of the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

JUDITH A. CURRY is the chair of the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. Her research interests include remote sensing, climate of the polar regions, atmospheric modeling, and air/sea interactions. She participates in the World Meteorological Organization's World Climate Research Program, was a member of the Science Steering Group of the Arctic Climate System Program, and chairs the Global Energy and Water Cycle Experiment Cloud System Studies Working Group on Polar Clouds. She co-chaired

the Surface Heat Budget of the Arctic Ocean program's Science Working Group. Dr. Curry previously served on the NRC Committee to Review NASA's Polar Geophysical Data Sets, the Panel on Coastal Meteorology, the Climate Research Committee, and the Space Studies Board. She was a member of the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

CRAIG J. DONLON is director of the International GODAE (Global Ocean Data Assimilation Experiment) High Resolution Sea Surface Temperature Pilot Project (GHRSST-PP) at the Meteorological Office Hadley Centre for Climate Prediction and Research in Exeter, England. He is also the JCOMM (Joint Commission for Oceanography and Marine Meteorology) Services Programme Area coordinator, and he is responsible for international coordination of Marine Safety Services, Marine Accident and Emergency Response Systems, Waves and Storm Surges, and Sea Ice. Dr. Donlon has expertise in international weather and climate programs and the creation of climate data records. His work has been recognized with awards that include the 2000 American Meteorological Society (AMS) Editors award for the *Journal of Atmospheric and Oceanic Technology*, the 1997 and 1994 Royal Society award for the 1997 and 1994 MUBEX experiment, and the 1989 European Commission Marie Curie Fellowship Award.

JUDITH L. LEAN has worked in the Naval Research Laboratory's Space Science Division since 1986, where her research focuses on the mechanisms, measurements, and modeling of variations in the Sun's radiative output and the effects of this variability on Earth's global climate and space weather. She is a guest investigator on NASA's Upper Atmosphere Research Satellite and the Living with a Star and Sun-Earth Connection programs. Dr. Lean has testified on the science of climate change before the U.S. Senate Committee on Energy and Natural Resources and the U.S. Senate Committee on Commerce, Science and Transportation Subcommittee on Science, Technology and Space. She is a fellow of the American Geophysical Union (AGU) and a member of the National Academy of Sciences, the International Association of Geomagnetism and Aeronomy, the American Astronomical Society (Solar Physics Division), and the AMS. Dr. Lean served on the NRC Committee on Radiative Forcing Effects on Climate, the Board on Atmospheric Sciences and Climate, and the Panel on Climate Variability and Change. She was a member of the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

BERRIEN MOORE III is a professor and the director of the Institute for the Study of Earth, Oceans, and Space at the 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 on several NASA advisory committees, and in 1987 he 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 the IGBP (SC-IGBP). As chair of the SC-IGBP (1998-2002), Dr. Moore served as a lead author for the Intergovernmental Panel on Climate Change's Third Assessment Report (2001). He chaired the 2001 Open Science Conference on Global Change in Amsterdam and is one of the four architects of the Amsterdam Declaration on Global Change. Dr. Moore has contributed actively to committees at the NRC, and served as co-chair of the NRC Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future. He is also a member of the Space Studies Board and served on the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

R. STEVEN NEREM is a professor of aerospace engineering sciences at the University of Colorado (UC) Boulder. He is also an associate director of the Colorado Center for Astrodynamics Research and a fellow of the Colorado Institute for Research in Environmental Sciences. Prior to joining UC in 2000, Dr. Nerem worked at NASA Goddard Space Flight Center as a geophysicist; prior to that, he was an associate professor at the University of Texas at Austin. He is a leader in geodetic and oceanographic research, and a specialist in satellite geodesy and its applications to solid-Earth physics, ocean dynamics, and related climate sciences. His work covers many of the areas of satellite geodesy, including satellite orbit determination, satellite remote sensing, geodetic techniques, gravity

field determination, vertical crustal motions, geocenter motion, time-variable gravity and application to Earth mass redistribution, ocean dynamics, ocean topography, and sea level change. He participated in several NASA flight projects including Lageos II, TOPEX/Poseidon, Jason-1, Pioneer Venus Orbiter, and Mars Observer. In 1995, Dr. Nerem was awarded NASA's Exceptional Scientific Achievement Medal for his research in the area of gravity field determination. He also received the 2006 American Geophysical Union Geodesy Section Award.

ANNE W. NOLIN is an associate professor of remote sensing and physical geography at Oregon State University (OSU). Prior to her appointment at OSU, Dr. Nolin was a research scientist at the National Snow and Ice Data Center, part of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder. Her research interests include snow hydrology, polar climatology, the martian polar ice caps, and remote sensing of snow and ice from airborne and spaceborne sensors. She is currently a member of the Multiangle Imaging SpectroRadiometer (MISR) Science Team and was a NASA principal investigator for the validation of snow albedo retrievals from MISR and MODIS (Moderate Resolution Imaging Spectroradiometer). Dr. Nolin served as vice chair of the NRC Panel on Water Resources and the Global Hydrologic Cycle.

JAY S. PEARLMAN is the chief engineer of Network Centric Operations (NCO) Programs and Technologies at the Boeing Company. Dr. Pearlman's background includes research program management and development of sensors, remote sensing, and information systems. He was Boeing's chief architect for the NOAA GOES-R study contract and the chief scientist for the Landsat Data Continuity contract. He was also deputy principal investigator for the NASA Hyperion Program. Dr. Pearlman is a Boeing technical fellow and is leading the NCO research and technology coordination. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE) and chair of the IEEE Committee on Earth Observation, and principal IEEE delegate to the Group on Earth Observation. He is active in promoting systems architecture and information system development for large-scale national and global applications, including advancing ocean and coastal information systems. Dr. Pearlman has more than 70 publications and 25 U.S. and international patents. He served on the NRC Panel on Enabling Concepts and Technologies of the Committee for the Review of NASA's Pioneering Revolutionary Technology Program and the Space Applications and Commercialization Steering Committee. He is currently a member of the Ocean Studies Board, and he served on the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

JOYCE E. PENNER is the Ralph J. Cicerone Distinguished University Professor of Atmospheric Science at the University of Michigan. Dr. Penner is a leading expert on the interactions of chemistry, aerosols, and their effects on the climate system. She has published more than 110 peer-reviewed articles and her most recent article focuses on understanding the effects of anthropogenic aerosols on climate. Prior to joining the University of Michigan, Dr. Penner served as division leader of the Global Climate Research Division at the Lawrence Livermore National Laboratory, where she developed simplified treatments for the sulfur cycle within a global climate model. She used this model to quantify the climate forcing and climate response from anthropogenic sulfate aerosols. Dr. Penner studies the effects of carbonaceous aerosols on the lifetime and precipitation efficiency of clouds. She also led a model study that evaluated the differences between satellite-derived estimates of aerosol forcing and model-derived estimates. Dr. Penner served as a member of the NRC Committee on Metrics for Global Change Research and as vice chair of the NRC Panel on Climate Variability and Change, and currently serves as a member of the Climate Research Committee.

JAMES F.W. PURDOM is a senior research scientist at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. Before joining CIRA in 2001, he spent 4 years as director of the Office of Research and Applications in NOAA's NESDIS. Dr. Purdom's research focuses on remote sensing of Earth and its environment, as well as the development and evolution of atmospheric convection, with emphasis on the study of mesoscale processes using satellite data. He received the U.S. Department of Commerce Silver Medal in 1994, the National Weather Association Special Award in 1996, the AMS Special Award in 1997, and the Presidential Rank Award in 2001. He served on the NRC Task Group on the Availability and Usefulness of NASA's Space

Mission Data. Dr. Purdom was a member of the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

CARL F. SCHUELER recently retired as the chief scientist at Raytheon Santa Barbara Remote Sensing. His expertise is in satellite remote sensing. Dr. Schueler has led advanced sensor development studies and proposals for polar and geosynchronous Earth observation, as well as planetary exploration. He is familiar with the VIIRS instrument, the key NPOESS instrument for land imaging and ocean color measurements. He managed the mid-1990s Defense Meteorological Satellite Program Block 6 studies and the Polar-orbiting Operational Environmental Satellite 2000 studies that led to Raytheon's participation in the NPOESS program. He also led Raytheon's successful efforts for the Aerosol Polarimeter Sensor to be flown on NASA's Glory mission and NPOESS. Dr. Schueler served as an executive advisor to the Environmental Research Institute of the Michigan International Conference series on Remote Sensing of Marine and Coastal Environments and as a member of the Advisory Committee of the University of California at Santa Barbara Institute for Computational Earth System Science. Dr. Schueler has served on five NRC committees, including the Panel on Weather.

GRAEME L. STEPHENS is a professor in the Department of Atmospheric Sciences at Colorado State University. His research activities focus on atmospheric radiation and on the application of remote sensing in climate research, with particular emphasis on understanding the role of hydrological processes in climate change. His other activities include the development of doppler lidar for measurement of boundary layer winds and studies in atmospheric visibility. Dr. Stephens is the principal investigator of NASA's Cloudsat Mission. He is the author of *Remote Sensing of the Lower Atmosphere: An Introduction* (Oxford University Press, 1994). His most recent NRC service includes membership on the Committee on the Future of Rainfall Measuring Missions, the Panel on Climate Change Feedbacks, and the Committee on Earth Studies.

CHRISTOPHER S. VELDEN is currently a research scientist at the University of Wisconsin where he heads a group that develops satellite products, mainly for tropical cyclone applications. He served as a member of the U.S. Weather Research Project Science Steering Committee (1996-1999), the GOES Science Team (1996-1998), and the Geostationary Microwave Sounder Working Group (1995-1996). Dr. Velden served as chair of the AMS Committee on Satellite Meteorology and has also been a member of the AMS Tropical Committee. In the last 5 years he has been honored by AMS with two awards and has published numerous papers. He served on the NRC Committee on NOAA-NESDIS Transition from Research to Operations, the Committee on the Future of the Tropical Rainfall Measuring Mission, the Panel on Weather, and the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

ROBERT A. WELLER is the director of the Cooperative Institute for Climate and Ocean Research at the Woods Hole Oceanographic Institution. His research focuses on atmospheric forcing, surface waves on the upper ocean, prediction of upper ocean variability, and the ocean's role in climate. Dr. Weller has been a pioneer in developing tools and technologies that enable scientists to investigate upper ocean processes on scales from meters to tens of kilometers and with accuracy never before available. In recognition of Dr. Weller's distinguished contributions to ocean science, he was named Secretary of the Navy/Chief of Naval Operations Oceanographic Research Chair by the Office of Naval Research. Dr. Weller has been on multiple mooring deployment cruises and has practical experience with ocean observation instruments. He is currently a co-chair of the U.S. Climate Variability and Change (CLIVAR) Scientific Steering Group and a member of the international CLIVAR Scientific Steering Group. He has served on several NRC committees, including the Committee to Review the U.S. Climate Change Science Program Strategic Plan, the Committee on Implementation of a Seafloor Observatory Network for Oceanographic Research, and the Committee on Utilization of Environmental Satellite Data: A Vision for 2010 and Beyond. He also served on the NRC Board on Atmospheric Sciences and Climate.

FRANK J. WENTZ serves as the director of Remote Sensing Systems, a research company specializing in satellite microwave remote sensing of Earth. His research focuses on radiative transfer models that relate satellite

observations to geophysical parameters, with the objective of providing reliable geophysical data sets to the Earth science community. He is currently working on satellite-derived decadal time series of atmospheric moisture and temperature, the measurement of sea-surface temperature through clouds, and advanced microwave sensor designs for climatological studies. Mr. Wentz served on the NRC Panel on Reconciling Temperature Observations of the Climate Research Committee and was a member of the Committee on Earth Studies. He also served as a member of the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

Consultant

STACEY W. BOLAND received her Ph.D. in mechanical engineering from the 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 for several community workshops. Dr. Boland has served as a consultant to the NRC Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future and to the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft.

Staff

ARTHUR CHARO, study director, joined the Space Studies Board as a senior program officer in 1995. He has directed studies that have resulted in some 30 reports, notably the first NRC decadal survey in solar and space physics (2002) and in Earth science and applications from space (2007). Dr. Charo received his Ph.D. in physics from Duke University in 1981 and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. He then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a research fellow from 1985 to 1988. From 1988 to 1995, he worked as a senior analyst and study director in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was the 1988-1989 American Institute of Physics AAAS Congressional Science Fellow. In addition to NRC reports, he is the author of research papers in molecular spectroscopy, reports on arms control and space policy, and the monograph *Continental Air Defense: A Neglected Dimension of Strategic Defense* (University Press of America, 1990).

THERESA M. FISHER is a program associate with SSB. During her 30 years with the Academies, she has held positions in the executive, editorial, and contract offices of the National Academy of Engineering and positions with several NRC boards, including the Energy Engineering Board, the Aeronautics and Space Engineering Board, the Board on Atmospheric Sciences and Climate, and the Marine Board.

CATHERINE A. GRUBER is an assistant editor with SSB. 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 worked as an outreach assistant for the NAS-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.