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

A Workshop Report

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Space Studies Board

Division on Engineering and Physical Sciences

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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

[1]Excerpted 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.

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

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

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.

[4]See 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.

[5]Presentations 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.

[6]The 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.

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

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,[9] 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.

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[8]The 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/.

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

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

[11]For 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.

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

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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APPENDIXES

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.[1] 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).

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

[2]See 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.

[3]In 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.

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

[4]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.

[5]In 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.

[6]See 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 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.

1

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.[1] 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.[2] 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]

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

[2]United 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.

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

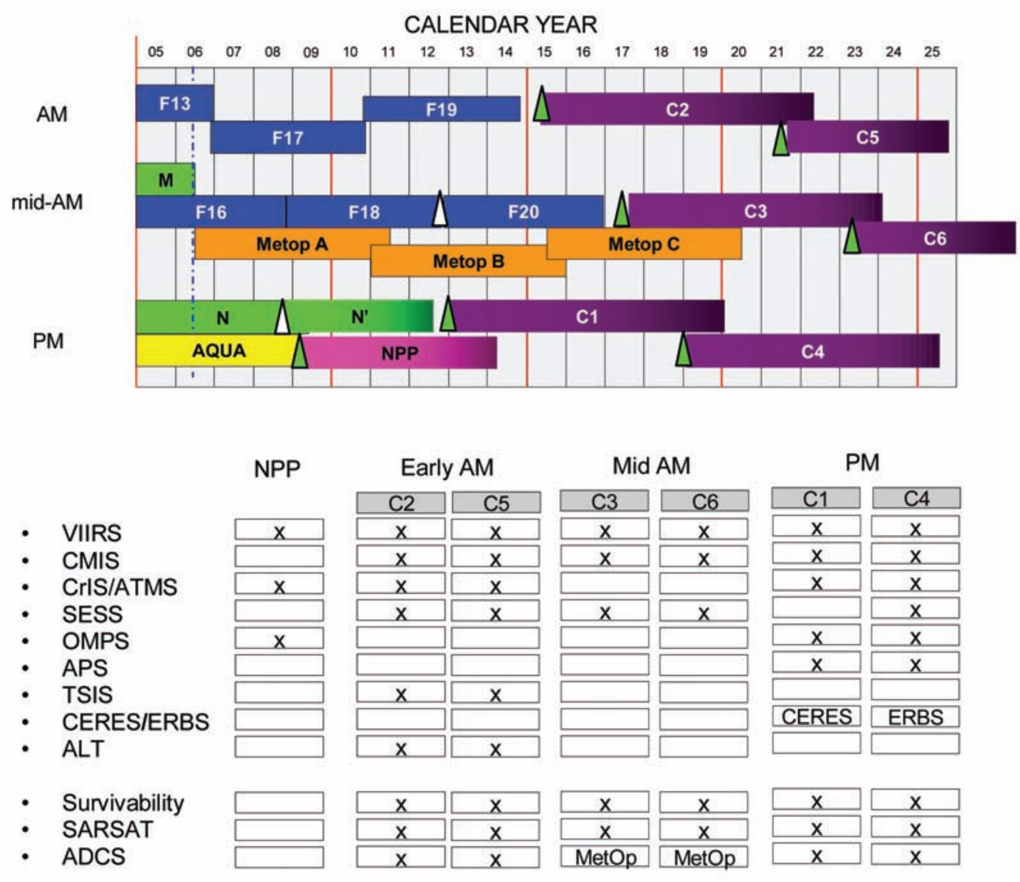

FIGURE 1.1 NPP and NPOESS program summary prior to the June 2006 Nunn-McCurdy program review and revisions. With the exception of CrIS, ATMS, and SESS, all key operational instruments, including SARSAT and ADCS, were intended to be flown on all three orbits. Climate and research-oriented sensors were 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

[4]For 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.

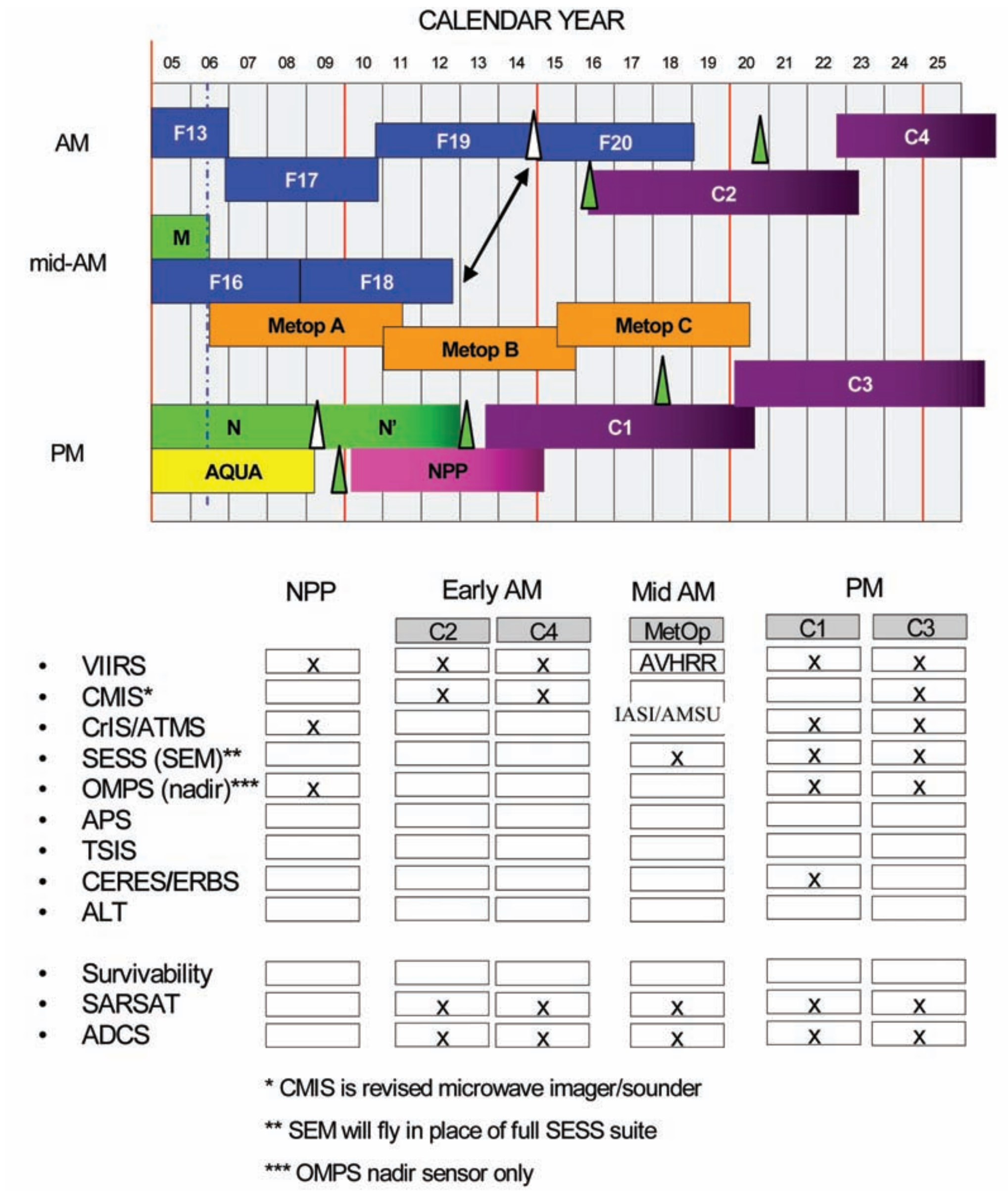

FIGURE 1.2 NPP and NPOESS program summary following the Nunn-McCurdy program review and revisions (status as of October 2006). The midmorning satellite coverage will be provided by the European MetOp satellite series, with descoped NPOESS satellites covering the early morning and afternoon orbits. Instruments 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.

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.

a 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]

[5]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 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.

[6]Developed 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 of

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.[7] 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.

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.pdf.

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

2

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.[1] 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 survey[2] might enable recovery of the NPOESS climate

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

[2]NRC, *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; upper-air 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.[4] 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

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[3]The filled-in templates are available at http://www7.nationalacademies.org/ssb/SSB_NPOESS2007_ Presentations.html.

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

[5]Intergovernmental 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 CO_2 and CH_4, 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 CO_2 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 CO_2 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 ASCAT[6] 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

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

MODIS 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.

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 obser-

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

vations 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.[8] 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.

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.

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

[9]In 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.

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, mesoscale 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.

Biomass

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).

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[10]It 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 CO_2 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.

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, mesoscale 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 unanswered 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).

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[11]The 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."

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

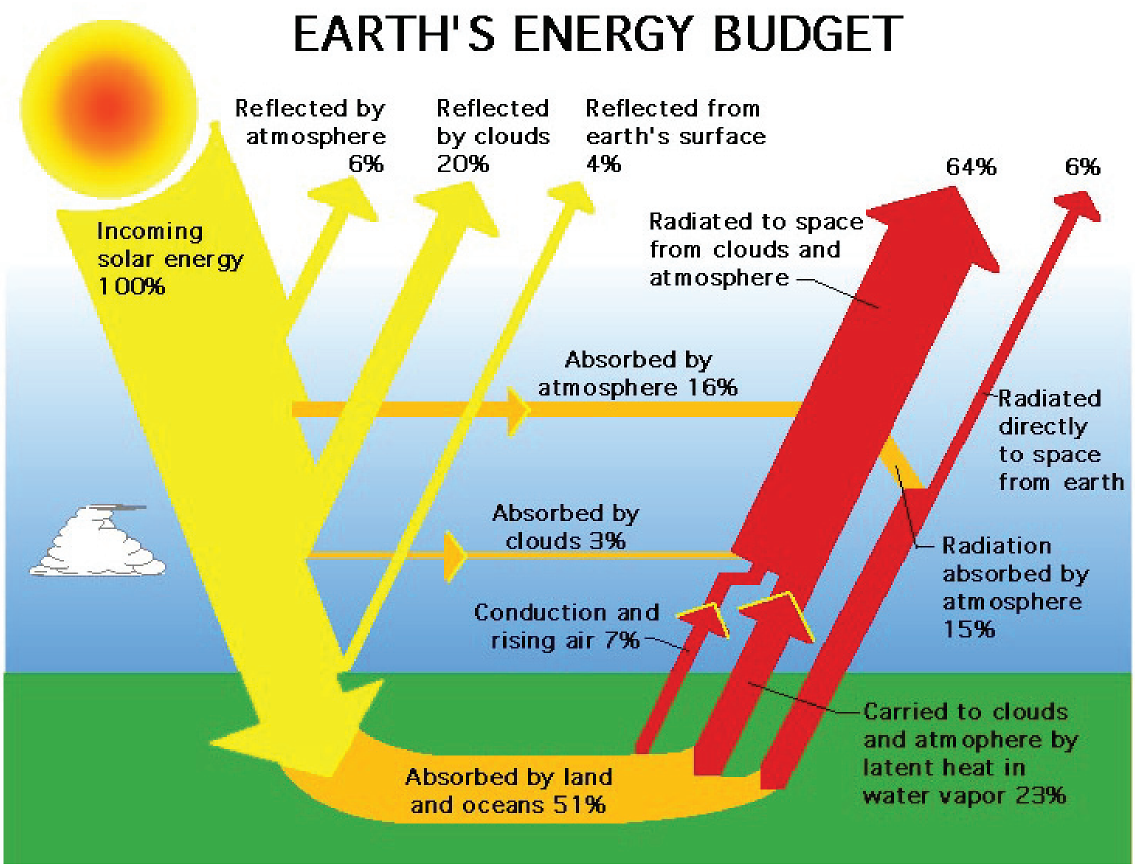

FIGURE 2.1 Diagram of Earth's radiation budget identifying the components that the three demanifested NPOESS sensors were to measure. SOURCE: After NASA Langley Research Center, "The Earth's Energy Budget," CERES S'COOL Project: Clouds and the Earth's Radiant Energy System Students' Cloud Observations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

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.

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

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

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]

[14]Physical 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.

[15]The 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.

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 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 (~40 km × 40 km). The GOME-II instrument also measures aerosols, NO_2, SO_2, 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 NPP[16]).

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.

[16]Press 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.

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 (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-like[17] 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.

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

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 2130 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.[18] 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.

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 orbit[19] 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

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

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

[20]J. 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.

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 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 H_2O (or CO_2). 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

[21]For 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.

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.

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 level[22] 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

[22]Technology 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.

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.

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:

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[23]The 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.

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."[24] WindSat is similar but not identical to CMIS, allowing insight into the accuracy of vector wind

[24]Windsat 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.

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.

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

[25] See, 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.

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.

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. Regardless 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.[26] 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.

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

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 Workshop[27] 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 extra-tropical 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 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 measure-

[27]The 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.

ments 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.

[28]For 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.

[29]P. 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.

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

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

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 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 (P^3I) 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

[32]Centrec 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.

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

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, 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

[34]Intergovernmental 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.

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:

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."[35] 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 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

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).

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

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

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.[b] 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).[f] 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.

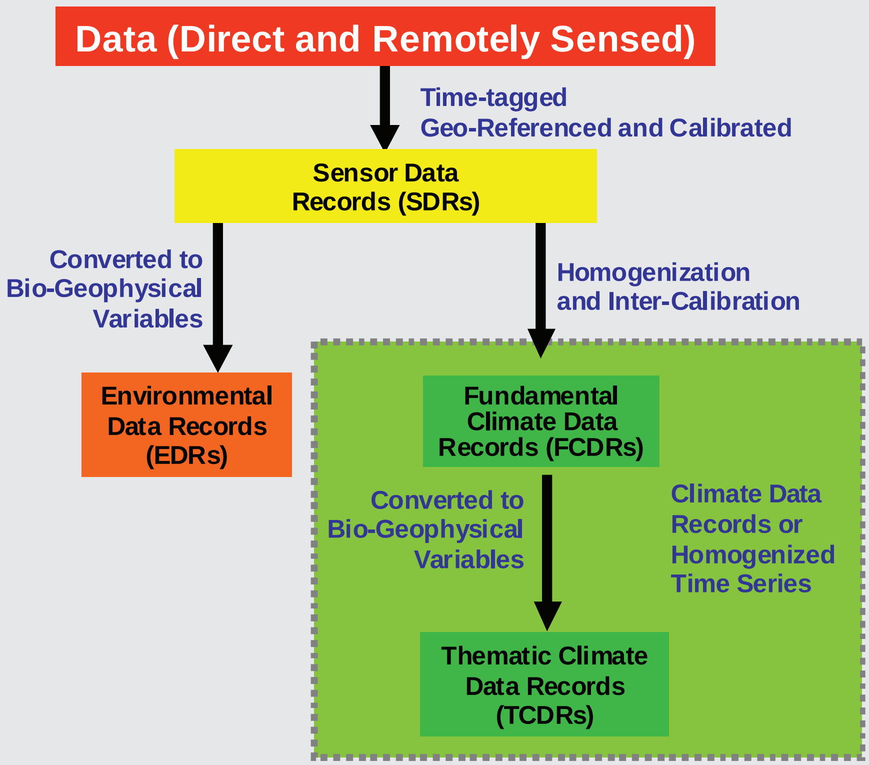

FIGURE 2.1.1 Pathways in the development of EDRs amd CDRs. SOURCE: J.J. Bates, NOAA National Climatic Data Center, "NPOESS EDRs vs. Climate Data Records (CDRs)," presentation to the Panel on Options to Ensure the Climate Record from the NPOESS and GOES-R Spacecraft, April 23, 2007.

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[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.

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. Participants also noted that where CDRs are particularly affected by the demanifesting of a sensor (e.g., APS), restoring the sensor without the capability for long-term CDR generation and maintenance is of little benefit.

The workshop breakout session discussion specifically avoided defining agency roles and responsibilities, consistent with the workshop's overall focus on identifying various options, but not their funding source. Further, the session participants suggested that the forthcoming National Research Council study on a strategy to mitigate the climate impacts that resulted from the NPOESS restructuring also avoid any attempt to assess costs or agency responsibilities, noting that these efforts should be initiated by the government in response to general study findings and recommendations regarding CDR generation requirements.

Personnel training and maintenance of scientific capability over the long term were cited as essential elements of successful CDR development. It was noted that although operational programs also require skill continuity, the types and levels of skills required for CDRs are substantially more demanding and therefore more expensive to maintain than those for EDRs.

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.[1] 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-

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

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). Pre-flight 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

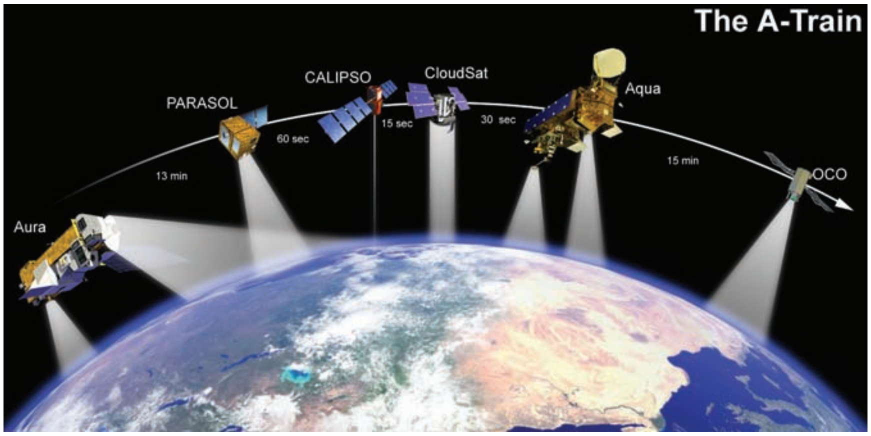

FIGURE 3.1 Artist's conception of the A-Train. The A-train satellites are, from left, Aura, PARASOL, CALIPSO, CloudSat, Aqua, and the Orbiting Carbon Observatory (OCO), which will lead the formation after its planned launch in 2008. SOURCE: NASA, Washington, D.C. Available at http://www.nasa.gov/mission_pages/cloudsat/multimedia/a-train.html.

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 view[2] 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

[2]A 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.

[3] NRC, *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.

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:

1. 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

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

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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)
  - 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

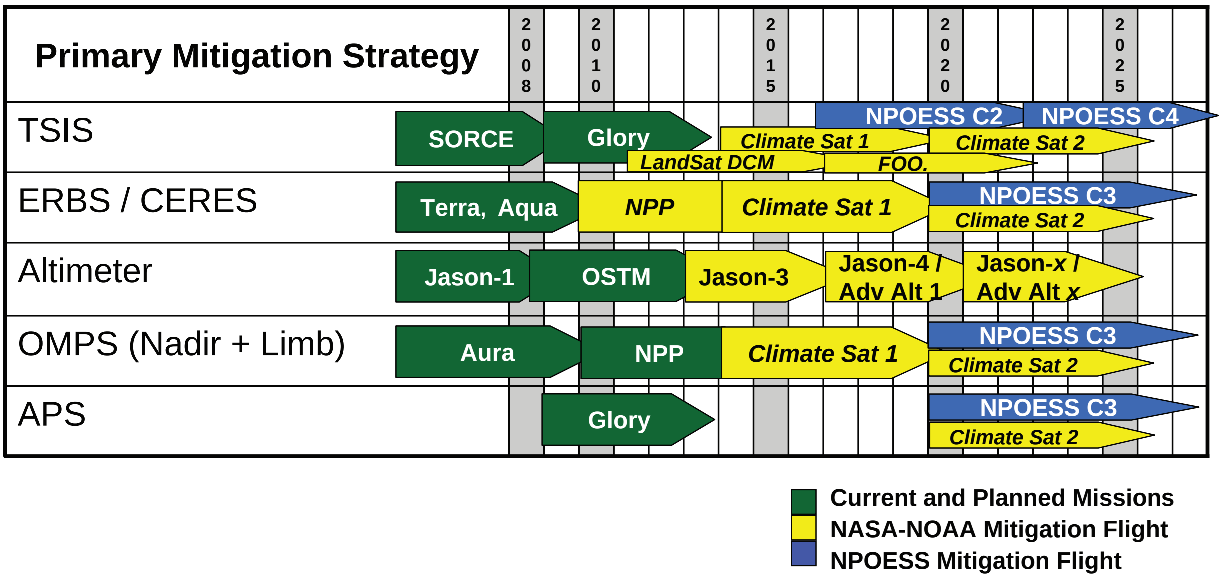

FIGURE [C.1] Range of Options Examined for Climate Data Continuity. [p. 7]

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:	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					
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]

NOTES:

- 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

OPTION # 1:

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					

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

FIGURE [C.3] Option 1. NPOESS + Climate Satellite. [p. 9]

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

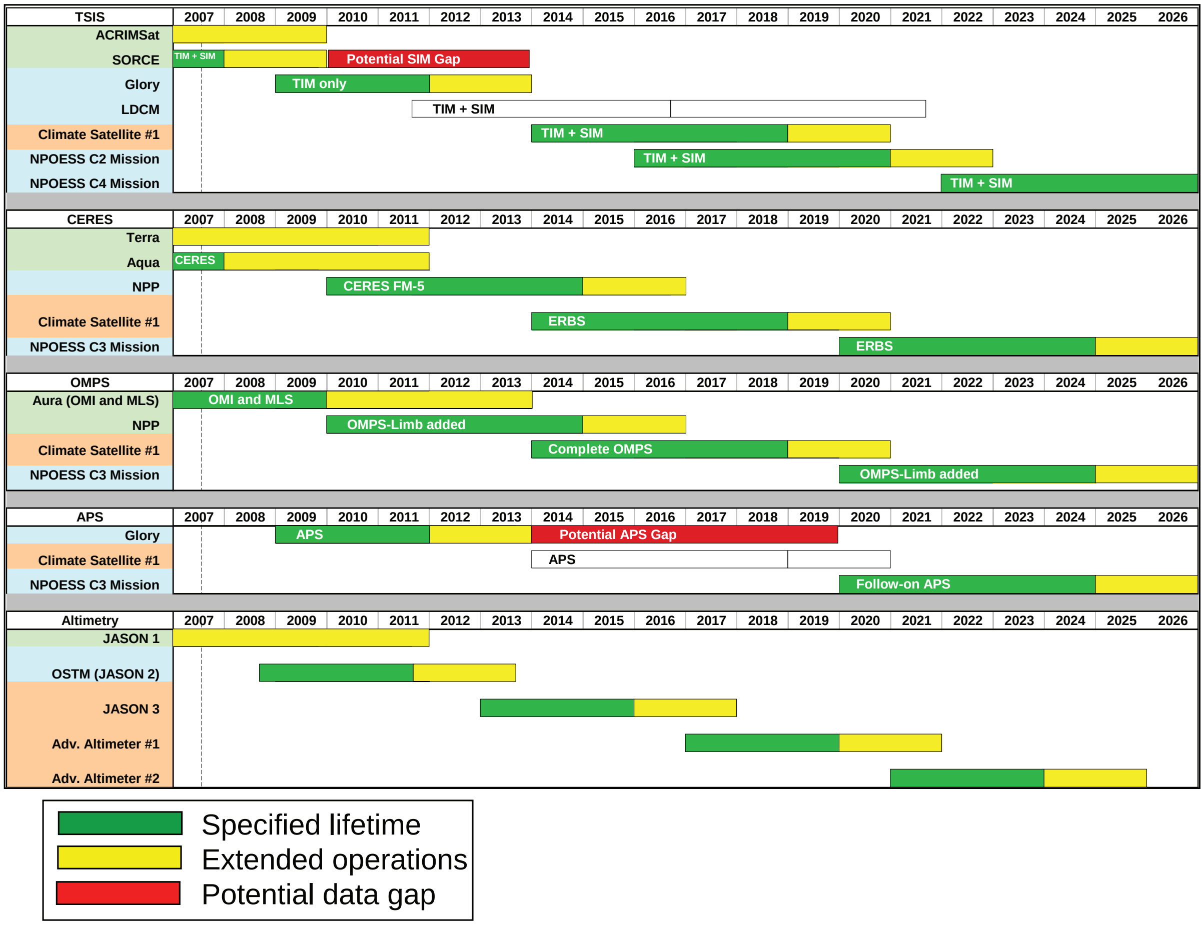

FIGURE [C.4] Option 1. Continuity Timeline. NPOESS + Climate Satellite. [p. 10]

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:

- (light blue) = Mission in Formulation or Development
- (orange) = Mission Concept to Restore NPOESS De-Manifested Climate Sensors
- (gray) = Mission Not Involved in this Option
- (light green) = 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					
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:
- [light blue] = Mission in Formulation or Development
- [orange] = Mission Concept to Restore NPOESS De-Manifested Climate Sensors
- [gray] = Mission Not Involved in this Option
- [light green] = 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

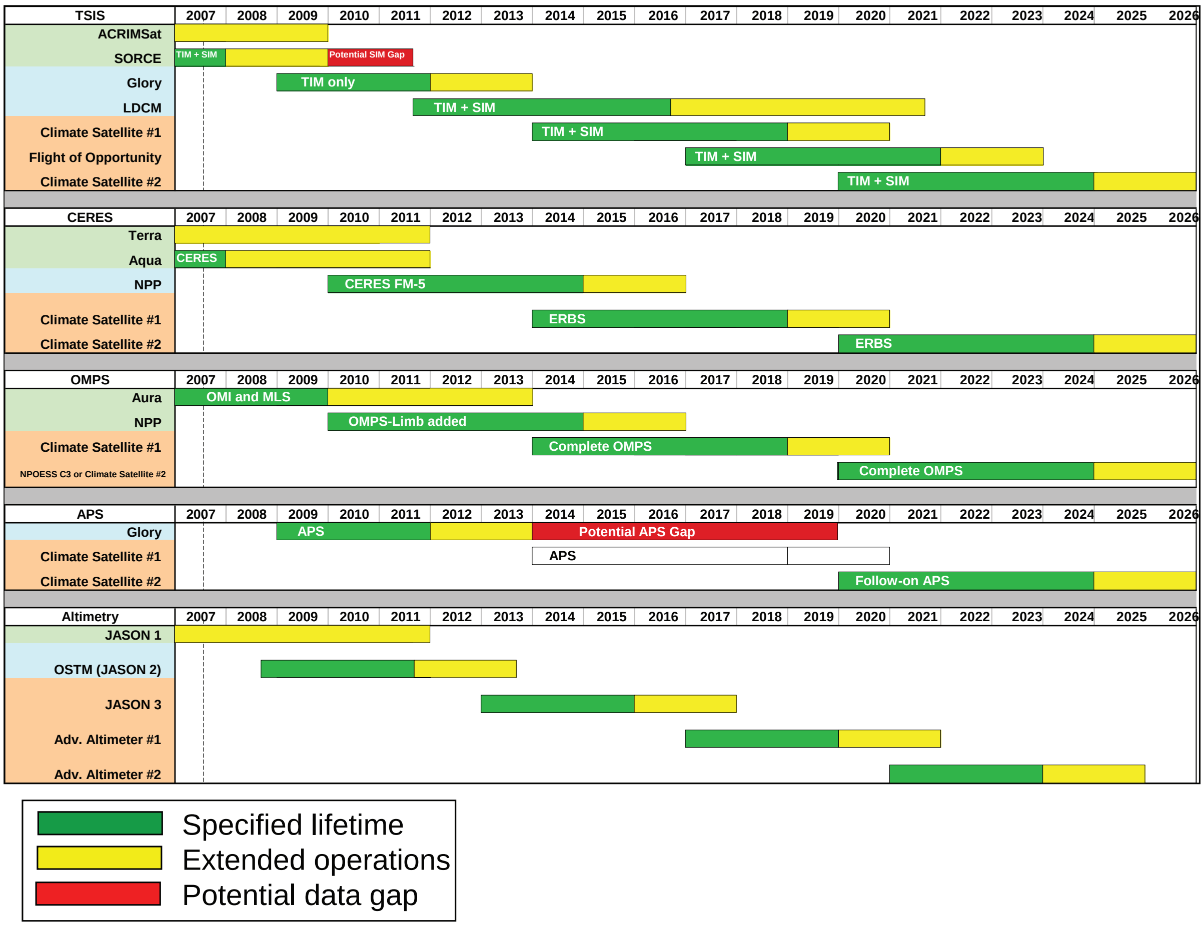

FIGURE [C.8] Option 3 and 4. Continuity Timeline. Sequential Climate Satellites + TSIS Redundancy. [p. 14]

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

- 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:
  - 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]

Increasing Potential ↑

Partner	Sensor or Capability	Timeframe	Role
EUMETSAT	Jason-3	2013-2018	Mitigate
NASA/Navy	Adv. Altimeter	TBD	Mitigate
ESA/JAXA (Earthcare)	APS/ERBS-like	2010-20xx	Mitigate
ESA GMES Sentinel 3	Altimeter		Complement
Navy (NPOESS)	Altimeter (Op)	2016-2026	Complement
Navy (DoD Space Test Program)	Altimeter (Op)		Complement
CNES Megha-Tropiques	ERBS-like		Complement
Chinese SOA (HY series)	Altimeter		Mitigate
Brazilian Space Agency (Amazonia)	Flight Opportunity	2010/2015	Accommodation
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

Backups [pp. 23-24]

NPOESS Instruments	NPP	EARLY-AM New C2 (2016) Old (C2) (2011)	EARLY-AM New C4 (2022) Old (C5) (2015)	MID-AM Old (C3) (2013)	MID-AM MetOp	MID-AM Old (C6) (2016)	PM New C1 (2013) Old (C1) (2009)	PM New C3 (2020) 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**
Reduced Capability **Related Missions**
Deleted ✓ **Implies Sensor Present**

***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 scatterometers
ASCENDS	Active Sensing of CO_2 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)
Meteosat	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
P^3I	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
SCLP	Snow and Cold Land Processes
SeaWiFS	Sea-Viewing Wide-Field Sensor
SESS	Space 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

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

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 co-investigator 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.