NOAA's ROLE IN SPACE-BASED GLOBAL PRECIPITATION ESTIMATION AND APPLICATION

Committee on the Future of Rainfall Measuring Missions

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

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Cover image: Artist's rendition of the NASA-JAXA Global Precipitation Measurement mission core satellite.

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Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Robert Dickinson, Georgia Institute of

Technology, Atlanta. 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 committee and the institution.

Contents

Summary

Continuous and reliable global precipitation information is crucial for myriad applications ranging from weather to climate, such as flood forecasting, understanding the inner workings of hurricanes and other storm systems, and tracking long-term trends in water supply. Measuring precipitation is, however, one of the more difficult observational challenges of meteorology because the phenomenon occurs with pronounced geographic and temporal variability. In conjunction with comprehensive, accurate ground validation and calibration, satellite observations offer the only realistic prospect for accurate and semicontinuous global precipitation data sets, especially over the oceans and in remote regions. Building on the progress from three decades of measuring or inferring precipitation from space—most recently with advances made by the Tropical Rainfall Measuring Mission (TRMM)—the upcoming Global Precipitation Measurement (GPM) mission represents the next generation of measurement capability for meeting the mission requirements at the National Oceanic and Atmospheric Administration (NOAA) for global precipitation data (NOAA, 2002).

This report offers analysis and recommendations to facilitate effective operational use of this next-generation precipitation measurement capability. At NOAA's request, the National Research Council's Committee on the Future of Rainfall Measuring Missions[1] was tasked to answer the following questions:

[1]This report is the second of two reports from the committee. In December 2004, the committee released *Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission: A Perspective from the Research and Operations Communities, Interim Report* (NRC, 2004). Because of TRMM's unique and substantial contributions to the research and operational communities, the committee recommended its continued operation. The National Aeronautics and Space Administration agreed with this recommendation, and TRMM was extended to at least fiscal year 2009. The possibility remains for TRMM to operate until its fuel runs out in approximately 2012.

1. What lessons were learned from TRMM with respect to operational uses of the data, and how can these lessons enhance the use of GPM mission data and other National Aeronautics and Space Administration (NASA) research mission data in NOAA operational forecasts?
2. What are the best uses for GPM data in an operational environment such as in NOAA?
3. How can NOAA ensure that its operational forecast models, forecasters, and product users are ready for GPM data as soon as possible after launch?

The GPM mission is a cooperative effort of NASA, the Japan Aerospace Exploration Agency (JAXA), NOAA, and other U.S. and international agencies and institutions.[2] The mission includes a core satellite that makes measurements between 65 degrees latitude North and South and carries a dual-frequency precipitation radar and a passive microwave sensor. The data from this satellite are to be intercalibrated with those from a constellation of other satellites carrying similar microwave sensors to provide global estimates of precipitation approximately every 3 hours. NASA conceives the GPM mission as a prototype for the Global Earth Observation System of Systems (GEOSS)—an international initiative for integrating data from numerous Earth-observing systems with similarities to the international and collaborative efforts of the GPM mission.

The GPM mission time line can be separated into three phases: the prelaunch phase runs from present to the launch date for the GPM core satellite (scheduled for 2013); the post-launch phase runs until NOAA potentially takes over operation of the core satellite from NASA (proposed for 5 years after launch, in approximately 2018); and the potential NOAA takeover phase then runs until the instruments fail on the core satellite or until fuel is depleted. NOAA has already indicated interest in the concept of this third phase, as well as the possibility of an operational GPM follow-on mission that overlaps with the GPM mission. As of the publication of this report, the design specifications could change to allow more fuel to be carried on the core satellite for the possibility of a longer mission.

Some of the constellation satellites will be launched prior to the GPM core satellite (Figure S.1), and some also will overlap with missions that form the present constellation of passive microwave sensors. The present-day, de facto passive microwave constellation represents a "golden era" of microwave precipitation sensing because the number of constellation satellites is likely to be small-

[2]The U.S. Department of Defense, Joint Center for Satellite Data Assimilation (JCSDA), Japanese Meteorological Agency, European Space Agency, Indian Space Research Organization, French Space Agency, China Meteorological Administration, International Precipitation Working Group (IPWG), the World Meteorological Organization, and the academic community.

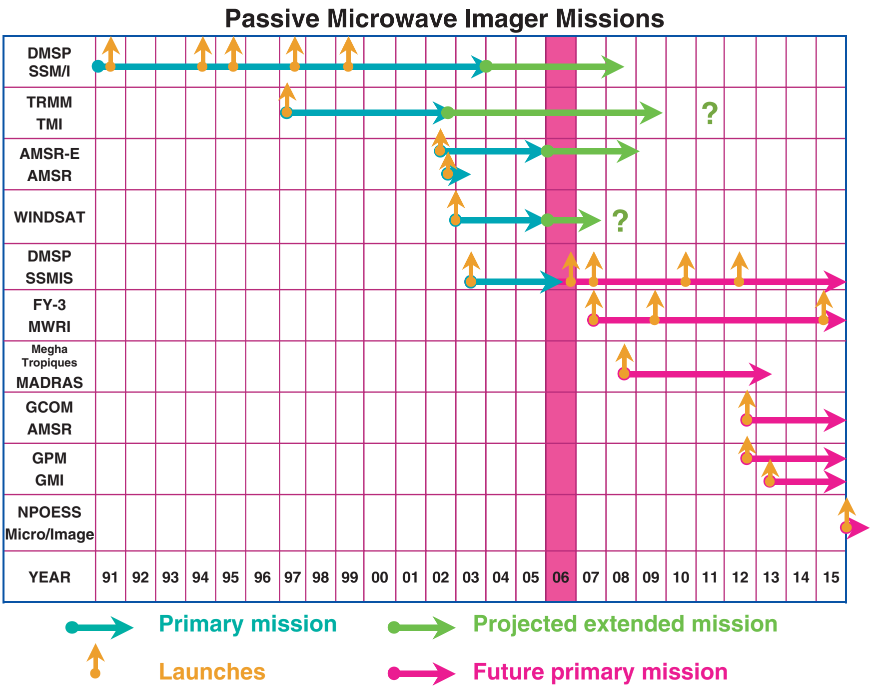

FIGURE S.1 Duration of primary missions of spaceborne passive microwave imagers and their potential extensions (see Appendix E for explanations of program acronyms). Question marks indicate the possibility of additional extensions beyond the projected extension. Future missions are subject to change.

er in the GPM era and the composition of the constellation is still unclear. The present constellation includes a suite of operational and research sensors that serve as an excellent testbed for discussion, planning, and demonstrations of GPM applications. In addition, the extension of TRMM to at least 2009 means that a GPM-like constellation already exists because there is already a core satellite (albeit with a more limited geographic coverage) carrying both a microwave radiometer and a precipitation radar. This provides NOAA and NASA with a superb opportunity to plan and carry out effective transitions early in their GPM collaboration and to test and refine methodologies in advance of the GPM core satellite launch. Such methodologies will help NOAA bridge the gap between its operational requirements and current measurement capabilities. The kinds of applications for which these (and, subsequently, GPM) data will be particularly valuable are numerical weather prediction (through improved data assimilation and moist physics approaches); monitoring tropical cyclones and severe storms; flash flood forecasting; calibrating ground-based precipitation networks; improving high-resolution, global precipitation analyses; and extending precipitation climatology (beyond the record started by TRMM) and climate data records of global precipitation.

LESSONS LEARNED FROM TRMM

Lessons learned from TRMM will guide observational and research aspects of the GPM mission, effective transition of GPM data and results to operational use, and partnership among NOAA, NASA, and other U.S. and international agencies and institutions. The overarching technological lesson of TRMM was its demonstration that inferring precipitation from space is sound. TRMM demonstrated the robustness, high endurance, and general feasibility of paired radar and passive microwave systems in space as well as the value of precipitation radar for observing the fine-scale, three-dimensional structure of precipitating weather systems. In addition, TRMM demonstrated the value of a multisensor reference satellite for calibrating data from other space-based observational systems and the feasibility of obtaining near-real-time global coverage of precipitation observations from space. Conversely, TRMM showed the difficulties of direct validation of its precipitation measurements using surface measurements but pointed the way toward better approaches in the GPM era. In general, TRMM is an example of unexpected "bonuses" often accruing from a scientific mission, and it was a model for international cooperation in pursuing a remote-sensing initiative.

TRMM generated a number of lessons that will improve planning for operational use of GPM data. The TRMM experience demonstrated that operational application of research data can be hampered if the mission has no specific application goals, no pre-launch planning for operational exploitation of the data, and uncertainty regarding the post-launch phase.

Lessons learned from the absence of such planning for TRMM have stimulated informal, pre-launch planning by NOAA for operational exploitation of GPM data. In addition, NOAA is participating in multiple, joint NASA-NOAA planning activities, namely, the NOAA-NASA GPM Research and Operations Group, NOAA participation on the NASA Precipitation Measurement Missions science team, the Joint Center for Satellite Data Assimilation (JCSDA), and the International Precipitation Working Group (IPWG). However, NOAA's participation in these partnering activities is ad hoc, lacking in formal funding, or outside of NOAA's control. These factors limit NOAA's ability to formally engage in GPM planning.

Given NOAA's interest in the concept of operating the GPM mission after the NASA post-launch phase and the value it will derive from GPM data in earlier stages of the mission, there is a need for more formal planning and involvement by NOAA. The Geostationary Operational Environmental Satellite-R

(GOES-R) Risk Reduction plan,[3] for example, includes preparations to reduce the risk of not being ready to use data once GOES-R is launched and fully functional, and to provide state-of-the-art software and algorithms to derive products from the data once they become available. This plan could serve as a model for many elements of NOAA's preparations for the GPM mission.

Recommendation: **As soon as possible, NOAA should formalize its GPM planning by developing a comprehensive, coordinated, agency-wide strategic plan for activities in all three phases of the GPM mission. In addition, NOAA and NASA should determine their respective roles and responsibilities in all three phases.** *(Relates to Recommendations 2.1, 3.1, 3.2, 4.3, 4.4, 4.5, and 5.2)*

Recommendation: **NOAA should consider the GOES-R strategic readiness approach as a model for aspects of its GPM strategic plan.** *(Recommendation 5.1)*

Recommendation: **NOAA should formally support the NOAA-NASA GPM Research and Operations Group, the NASA Precipitation Measurement Missions (PMM) science team, JCSDA, and IPWG through the establishment of a NOAA steering group on space-based precipitation missions, through direct support of these partnership activities, and/or through support of individual NOAA scientists. The NOAA steering group on space-based precipitation missions should serve as a focal point at NOAA to coordinate GPM partnership activities with NASA and should oversee implementation of the GPM strategic plan recommended by this committee.** *(Relates to Recommendations 3.3, 3.4, 3.6, 4.1, 4.2, 4.6, and 4.7)*

BEST USES OF GPM DATA AT NOAA

To identify the best uses of GPM mission data at NOAA, the committee examines NOAA mission requirements for precipitation data and related products. Next, the committee identifies current sources and applications of NOAA operational precipitation data and recommends improvements in preparation for GPM. The best operational uses of GPM data at NOAA will be weather forecasting, hydrologic applications, climate applications, and global precipitation climate data records.

[3] See "The NOAA GOES-R Risk Reduction Plan," unpublished document, P. Menzel (NOAA), 2006.

PREPARATIONS FOR THE GPM MISSION AND BEYOND

The committee identified 11 areas of activity for NOAA's preparations for the GPM mission: (1) NASA-NOAA cooperative research and development, (2) data exchange, (3) intercalibration, (4) ground validation support, (5) data product development, (6) data archiving and distribution, (7) infusion of new technology, (8) data assimilation, (9) model physics development, (10) data impact evaluation, and (11) user education and training. In addition to the concepts and actions that NOAA has already expressed interest in pursuing (e.g., GPM follow-on activities), the committee recommends additional, detailed guidance for activities in preparation for the GPM mission. These activities and recommendations are listed within the three-phase framework of the GPM mission (Table S.1). Because the committee's third task focuses on the pre-launch phase of the GPM mission, many of the recommendations in Table S.1 are listed under the pre-launch phase.

The transition of the GPM mission from a research program to an operational system will have to be designed to ensure continued acquisition and application of high-quality, intercalibrated global satellite-based precipitation observations in support of NOAA's mission-oriented forecasting operations and climate services. This will involve four areas of effort: (1) GPM core satellite and constellation satellites, (2) continuation of an intercalibration program, (3) continuation and expansion of an international ground validation program, and (4) development of a suite of data and data products.

> *Recommendation:* **NOAA's strategic planning for GPM should address the need for the development and implementation of operational versions of the four basic components of the GPM research program.**

Although the future state of operational global precipitation measurements is unclear, NOAA has the opportunity to lead and catalyze development of an operational precipitation measurement network in addition to supporting and working on the next-generation observational efforts that are planned for the GPM mission. NOAA's resources could be directed at many activities that will help in this regard (Table S.1), and the present constellation of passive microwave sensors in conjunction with TRMM's unique suite of sensors provides an ideal source of global, intercalibrated data with which to refine operational applications in preparation for future precipitation-measuring missions.

TABLE S.1 Proposed NOAA Activities During Pre-launch, Post-launch, and Potential NOAA-Takeover Phases of the GPM Mission

Phase	Category of Activity	Action
Pre-launch	Initiation and participation	• **Formally support the NOAA-NASA GPM Research and Operations Group, the NASA Precipitation Measurement Missions science team, JCSDA, and IPWG through the establishment of a NOAA steering group on space-based precipitation missions, through direct support of these partnership activities, and/or through support of individual NOAA scientists. The NOAA steering group on space-based precipitation missions should serve as a focal point at NOAA to coordinate GPM partnership activities with NASA and should oversee the implementation of the GPM strategic plan recommended by this committee. (4.1)**[a] • **Formally support contributions of NOAA scientists to IPWG so that NOAA's GPM program will help lead IPWG to the next generation. NOAA should fully fund its IPWG collaborations and ensure that its multisensor precipitation techniques result in state-of-the-art operational rain rate algorithms. (3.6)** • **Support precipitation assimilation work through JCSDA. (4.6)** • **Enhance research and development on data assimilation and moist physics parameterizations in models using proxy data from TRMM to test performance. (4.4)** • **Make full use of all microwave channels through better characterization of the surface emission, including higher frequencies over oceans (e.g., 165 and 183 GHz). Construct high-quality satellite and in situ data sets to fully assess radiative transfer model performance. (4.5)** • **Support participation of NOAA data assimilation scientists on sensor design and calibration-validation teams. In addition, encourage collaboration among assimilation scientists, precipitation algorithm developers, and personnel involved in large inter-related projects. (4.7)**

continued

TABLE S.1 Continued

Phase	Category of Activity	Action
		• **Develop strategies for meeting the archiving needs of the GPM era. (4.3)**
		• **Communicate to the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program office the critical role the NPOESS microwave imager will play in NOAA's GPM and GEOSS efforts. NOAA's strategic plan for GPM should include NPOESS contingency plans. (3.3)**
		• **Use NOAA's influence to facilitate free and swift access to all microwave imager digital data sets, whether they be from U.S. missions or foreign satellites. NOAA should use its international influence to encourage foreign collaborators in order to create a robust microwave satellite constellation. (3.4)**
		• **Take a leadership role in the international satellite community by proposing specific actions for the accurate calibration of all microwave imagers and sounders through cross-calibration and standard reference data sets and for implementing *internal* calibrations on all future microwave sensors. (3.5)**
		• **Strengthen rain gauge and radar networks and integrate the data into GPM calibration and validation efforts. (3.1, 3.2)**
		• **Explore ways of contributing observational assets and experience in site selection, modeling, and algorithm development to the GPM ground validation efforts. In addition, and in partnership with NASA and other entities, explore a comprehensive approach to international ground validation activities. (4.2)**
		• Develop research partnerships and support universities to fully exploit the developing ability to infer precipitation and associated physical and dynamical processes from space-based observations. (Chapter 3)

TABLE S.1 Continued

Phase	Category of Activity	Action
		• Host (with NASA) user conferences to familiarize and educate potential customers on the types of data and products that will become available. (Chapter 4)
	Planning and preparatory	• **Formalize GPM planning by developing a comprehensive, coordinated, agency-wide strategic plan for activities in all three phases of the GPM mission (including a plan for the transition of GPM from a research program to an operational system). Determine, with NASA, each agency's respective roles and responsibilities in all three phases. (2.1)**
		• **Consider the GOES-R strategic readiness approach as a model for aspects of the NOAA GPM plan. (5.1)**
		• Begin to develop the infrastructure and throughput requirements for the real-time receipt of data at the ingest port to NOAA computers and the product development interface. (Chapter 4)
		• Properly support product development activities so algorithm testing and advancement can occur by the launch of the GPM core satellite. (Chapter 4)
		• Plan for building up NOAA computing capacity so it is ready when needed. (Chapter 4)
Post-launch	Initiation and participation	• Develop full awareness of GPM data characteristics. (Chapter 4)
		• Receive GPM data in real time. (Chapter 4)
		• Evaluate the potential for assimilation and model improvements to handle GPM data and implement those that have potential to improve the value of the data, including computer processing power needs and data storage capacity for the operational phase. (Chapter 4)
		• Host (with NASA) enhanced algorithms and user conferences to promote user education, training, and feedback. (Chapter 4)

continued

TABLE S.1 Continued

Phase	Category of Activity	Action
	Planning and preparatory	• **Develop a follow-on NOAA program for the time after GPM ends and prepare to lead building this constellation; view U.S. contributions as components of a continuing and evolving international constellation of satellites; pursue efforts within the World Meteorological Organization and the Coordination Group for Meteorological Satellites to strengthen support for an operational program of satellite-based global precipitation measurements. (5.2)** • Establish budget requests for operating the satellite(s) so that resources are in place for the potential NOAA takeover phase. (Chapter 5)
Potential NOAA takeover	Initiation and participation	• Operate the GPM core satellite and U.S. satellite contributions to the constellation. (Chapter 5) • Process data in real time and deliver products to the operational and research user community. (Chapter 5) • Use error characterization for retrieval algorithms and data assimilation applications from the GPM ground validation program. (Chapter 2) • Begin building the GPM follow-on operational system. (Chapter 5) • Implement the follow-on operational constellation near the end of this phase. (Chapter 5)

NOTE: These activities are discussed in Chapters 3, 4, and 5 of this report; activities associated with a specific committee recommendation are listed in boldface type.

[a]Each recommendation in the chapters of this report is assigned a reference number. The first digit of the reference number corresponds to the chapter in which the recommendation appears (Chapter 2, 3, 4, or 5). The second digit of the reference number corresponds to the sequential order in which the recommendation appears within its chapter.

1

Introduction

Continuous and reliable global precipitation information is crucial for myriad applications ranging from weather to climate, such as flood forecasting, understanding the inner workings of hurricanes and other storm systems, and tracking long-term trends in water supply. However, measuring precipitation is one of the more difficult observational challenges of meteorology because precipitation occurs intermittently and with pronounced geographic and temporal variability. Surface observations alone are inadequate for observing precipitation globally.[1] Satellite-based sensors, on the other hand, can observe the entire Earth. In conjunction with comprehensive, accurate ground validation and calibration, satellite observations offer the only realistic prospect for accurate and continuous measurement of global precipitation.

Building on the progress from three decades of measuring or inferring precipitation from space—most recently the advances made by the Tropical Rainfall Measuring Mission (TRMM)—the upcoming Global Precipitation Measurement (GPM) mission constitutes the next generation of satellite-based precipitation estimates that will offer global coverage with a 3-hour refresh rate. The GPM mission is a cooperative effort of the National Aeronautics and Space Administration (NASA), the Japan Aerospace Exploration Agency (JAXA), the National Oceanic and Atmospheric Administration (NOAA), and other U.S.

[1] With few exceptions, surface-based precipitation measurements are essentially nonexistent over the 71 percent of Earth's surface covered by oceans. Even over large portions of the continents, there are both inadequate spatial sampling and inconsistent surface-based measurement of precipitation.

and international agencies and institutions,[2] and is considered a prototype for the Global Earth Observation System of Systems (GEOSS). NOAA asked the National Academies to prepare this report on the applications of satellite-based precipitation measurements in 2006 and beyond.

REPORT FOCUS

The National Academies' Committee on the Future of Rainfall Measuring Missions was tasked by NOAA to address three questions:

1. What lessons were learned from TRMM with respect to operational uses of the data, and how can these lessons enhance the use of GPM mission data and other NASA research mission data in NOAA operational forecasts?
2. What are the best uses for GPM data in an operational environment such as in NOAA?
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This report is the second of two reports from the Committee on the Future of Rainfall Measuring Missions. In December 2004, the committee released *Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission: A Perspective from the Research and Operations Communities, Interim Report* (NRC, 2004). Because of TRMM's unique and substantial contributions to the research and operational communities, the committee recommended its continued operation. NASA agreed with this recommendation, and TRMM was extended to at least fiscal year 2009. The possibility remains for TRMM to operate until its fuel runs out in approximately 2012.

This report contains five chapters. The first chapter provides an overview of the GPM mission and related international activities. Chapter 2 presents lessons learned from TRMM and how these lessons can apply to the use of GPM mission data at NOAA (Task 1). Chapter 3 presents ideas on the best uses of space-based precipitation data in an operational environment (Task 2). Chapter 3 also describes present and future sources of precipitation data for NOAA and presents ideas on how these sources could be enhanced to support operational global precipitation analyses (a facet of Task 3). Chapter 4 provides guidance for the early exploitation of precipitation data from future space-based missions

[2] DOD (U.S. Department of Defense), JCSDA (Joint Center for Satellite Data Assimilation), JMA (Japan Meteorological Agency), ESA (European Space Agency), ISRO (Indian Space Research Organization), French Space Agency, China Meteorological Administration, IPWG (International Precipitation Working Group), WMO (World Meteorological Organization), and the non-governmental research community.

BOX 1.1
GPM Science Objectives

- Advancing precipitation measurement capability from space through combined use of active and wide-band passive remote-sensing techniques
- Advancing understanding of global water-energy cycle variability and freshwater availability through better measurement of the space-time variability of global precipitation
- Improving weather forecasting skills through more accurate and frequent measurement of instantaneous rain rates
- Improving climate modeling and prediction capabilities through better understanding of precipitation microphysics, surface water fluxes, soil moisture storage, and atmospheric latent heating distribution
- Improving prediction capabilities for floods, droughts, fresh water resources, crop conditions, and other water-related applications through improved temporal sampling and high-resolution spatial coverage

SOURCE: Hou, 2005.

(Task 3). Finally, Chapter 5 outlines key aspects of a potential NOAA strategic plan for the three phases of the GPM mission. The report's appendixes include background information about NOAA-NASA collaboration on GPM, NOAA's goals with relevance to GPM, and legislation requiring NOAA-NASA participation in a Joint Working Group on research to operations.

THE GLOBAL PRECIPITATION MEASUREMENT MISSION

The GPM mission is the successor to TRMM. It is planned to include a core satellite (proposed for launch in 2013 as of publication) and data from several "constellation" satellites already in orbit that together will help us understand the horizontal, vertical, and temporal structure of precipitation. Like TRMM, it will have NOAA operational applications. Unlike TRMM, these applications are being formally planned well in advance of core satellite launch. GPM is a science program (Box 1.1) with integrated applications goals. It is a program of observations and basic and applied research aimed at improved weather, climate, and hydrologic predictions through application of more accurate and frequent precipitation measurements (Smith et al., 2004). The NRC Committee on Earth Science and Applications from Space has recommended GPM as one of two NASA missions that should proceed immediately[3] (see Box 1.2).

[3]Atmospheric Soundings from Geostationary Orbit (GIFTS) is the other mission.

BOX 1.2
GPM Recommendation from
Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation

"The Global Precipitation Measurement mission is an international effort to improve climate, weather, and hydrological predictions through more accurate and more frequent precipitation measurements. GPM science will be conducted through an international partnership lead by NASA and the Japan Aerospace Exploration Agency (JAXA). Water cycling and the availability of fresh water resources, including their predicted states, are of critical concern to all nations, and precipitation is the fundamental driver of virtually all water issues, including those concerned with national security. GPM is the follow-on to the highly successful Tropical Rainfall Measuring Mission, which is nearing the end of operations. It is an approved mission that has been delayed several times by NASA.

"The committee recommends that the Global Precipitation Measurement mission be launched without further delays."

SOURCE: NRC, 2005.

FOUR COMPONENTS OF THE GPM MISSION

There are four major components of the GPM mission (Figure 1.1): the core satellite, the constellation satellites that are calibrated by the core satellite, the precipitation processing system, and the international ground validation research program. NASA will contribute the GPM core satellite (in collaboration with JAXA) and will operate the mission following the launch. NOAA may have the option of taking over the operation of the GPM mission from NASA and operating the mission until the core satellite instruments are no longer producing useful data.

GPM Core Satellite

The core satellite is a collaborative effort between NASA and JAXA and will serve as the calibration reference system for the constellation of satellites and fundamental microphysics probe for the mission. It will fly in a non-sun-synchronous, inclined orbit of 65 degrees latitude (compared with the 35-degree inclined orbit of TRMM). The satellite will fly in a low orbit (400 km), similar to TRMM, to obtain fine-scale spatial resolution microwave measurements. The satellite will carry two advanced instruments:

1. **Dual-frequency precipitation radar** based on many of the successful technologies implemented on TRMM's precipitation radar. Operational frequencies of the precipitation radar are 13.6 GHz (Ku band; 245 km swath width) and

OBJECTIVES
- Understand horizontal and vertical structure and microphysical properties of precipitation, and associated latent heating
- Train and calibrate retrieval algorithms for constellation radiometers
- Provide global coverage and temporal sampling to improve rainfall accumulations and real-time precipitation monitoring
- Extend scientific and societal applications

Core Satellite
- TRMM-like spacecraft (NASA)
- H2-A rocket launch (TBC, JAXA)
- Non-sun-synch orbit
  ~ 65° inclination
  ~ 407 km altitude
- Dual frequency radar (JAXA)
  Ku-Ka Bands (13.6-35.5 GHz)
  ~ 4 km horizontal resolution
  ~ 250 m vertical resolution
- Multifrequency radiometer (NASA)
  10.65, 18.7, 23.8, 36.5, 89, 166, 183.3 GHz

Constellation Satellites
- Pre-existing operational-experimental and dedicated satellites with PMW radiometers and sounders
- Revisit time
  ~ 2-4 hour at > 80% of time
- Sun-synch and non-sun-synch orbits 600-900 km altitudes
- A real-time hurricane monitor in a low-inclination orbit (TCB, NASA)

Precipitation Processing System
- Global precipitation products from input data provided by a consortium of cooperative international partners

Ground Validation Sites
- Ground measurement and calibration
- Cooperative international partners

FIGURE 1.1 GPM Reference Concept. SOURCE: Adapted from Hou, 2005.

35.55 GHz (Ka band; 120 km swath width). The 13.6 GHz antenna-radar will be similar to the 13.8 GHz antenna-radar deployed on TRMM.

2. Large-aperture (high-resolution), conical-scanning, multichannel **passive microwave rain radiometer** (called the GPM Microwave Imager), with a 858 km swath width. The GPM Microwave Imager will make simultaneous measurements in several microwave frequencies (e.g., 10.7, 19.3, 21, 37, and 89 GHz), giving the instrument the capability to measure a variety of rainfall rates and related environmental parameters. There are also plans to provide experimental, higher-frequency channels (165 and 183 GHz) that enable the detection of light rain and snow (NASA, 2006a).

Co-location of the precipitation radar with the GPM Microwave Imager provides the opportunity to use the radar to make high-precision measurements of clouds, cloud structure, and rainfall processes and to compare these high-precision measurements with the radiometric measurements made by the GPM Microwave Imager. This process can then be extended to the members of the GPM constellation at orbital intersections (Flaming, 2004).

GPM Constellation Satellites

The planned observational system includes an array of satellites that has been called a "constellation of opportunity" (Smith et al., 2004). Each member of the constellation will carry one or more precipitation-sensing instruments, one of which will be a multichannel passive microwave radiometer that infers precipitation at several frequencies. The points of intersection of each constellation member's orbits with that of the core satellite will allow cross-sensor calibration and validation that will provide consistent and stable precipitation estimates among constellation members.

Potential constellation members with passive microwave imagers are shown in Figure 1.2. These are described in detail in Chapter 3 and may include satellites from the Defense Meteorological Satellite Program (DMSP), the National Polar-orbiting Operational Environmental Satellite System (NPOESS), the Japa-

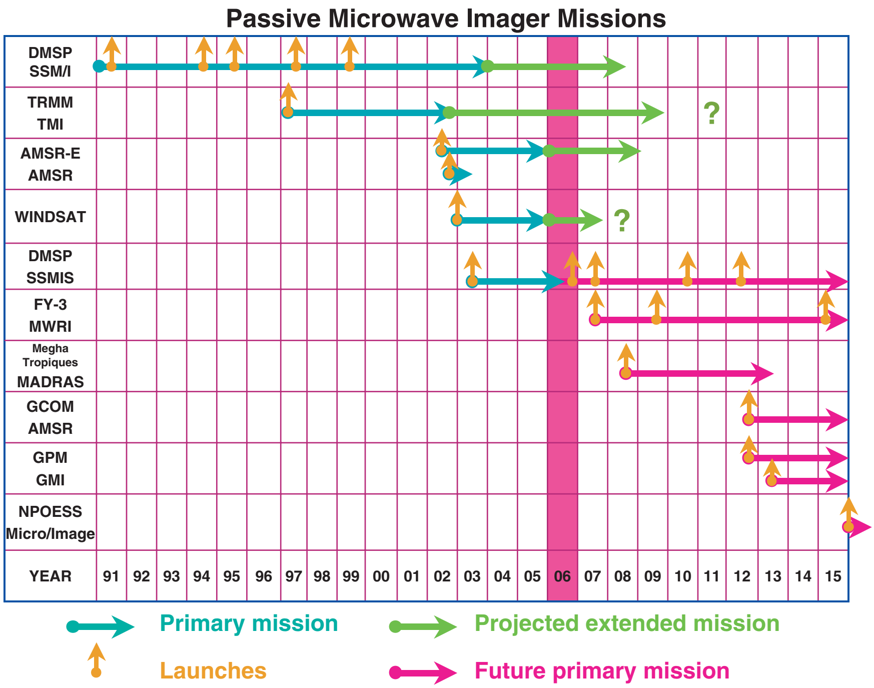

FIGURE 1.2 Duration of primary missions of spaceborne passive microwave imagers and their potential extensions (see Appendix E for explanations of program acronyms). Question marks indicate the possibility of additional extensions beyond the projected extension. Future missions are subject to change.

nese Global Change Observing Mission, the French-Indian Megha Tropique mission, the Chinese Fengyun-3 mission, and the European GPM mission (considered unlikely). The GPM constellation may also include geosynchronous imagers and microwave sounders.

Some of these constellation satellites will be launched prior to the core satellite (Figure 1.2), and some also would overlap with missions that form the present constellation of passive microwave imagers (Figure 1.2). The fortuitous overlap of DMSP operational sensors with research sensors in the last decade (i.e., TRMM Microwave Imager, Advanced Microwave Scanning Radiometer for the Earth Observing System [AMSR-E], and WindSat) has resulted in combined access to up to seven passive microwave sensors in near real time. This de facto passive microwave constellation represents a "golden era" of microwave precipitation sensing (because uncertainties in some of the planned missions mean that there will likely be fewer sensors in space when the GPM core satellite is launched). This present suite of operational and research sensors serves as an excellent testbed for GPM application discussion, planning, and demonstrations. In addition, the extension of TRMM and the existence of CloudSat and the A-Train means that a GPM-like constellation—complete with a core, radar-carrying satellite with paired microwave sensors—already exists for both the tropics and the mid to high latitudes. This provides NOAA and NASA with a unique and unprecedented opportunity to plan and carry out effective transitions early in their GPM collaboration. If TRMM and GPM overlap, the TRMM Microwave Imager would be an additional member of the GPM constellation. In addition, cross-calibration of the TRMM and GPM systems would be possible, and TRMM's climatological time series that began in 1997 would continue with no data gaps into the GPM era.

The GPM Precipitation Processing System

The GPM Precipitation Processing System will serve as the rapid science data-processing facility for precipitation missions within NASA and partner institutions. It will be capable of producing global precipitation data products from the diverse sensors and sources that are provided by NASA and cooperative international partners.

The International Ground Validation Research Program

In conjunction with the cross-calibration of the constellation instruments and the core satellite, the overall strategy for the GPM calibration and validation program will involve a ground validation program. This program will characterize errors, quantify measurement uncertainty, and provide a measurement standard against which to assess performance and aid in the improvement of the retrieval algorithms. A global ground validation network is necessary because of the variability in the types of precipitation (effects of precipitation type, topography, latitude, etc.). A global distribution of cooperative international sites is planned to provide the ground measurements required for calibration (Bidwell et al., 2004; Flaming, 2004).

Three types of ground validation sites are planned (Hou, 2005): (1) surface precipitation statistical validation sites for direct assessment of GPM satellite data products, (2) precipitation process sites for improving understanding and modeling of precipitation physics in physical and radiance spaces for satellite retrieval algorithm improvements, and (3) integrated hydrological sites for improving hydrological applications.

THREE PHASES OF THE GPM MISSION

The GPM mission time line can be separated into three phases (Figure 1.3). The **pre-launch phase** runs from the present up to the launch date of the GPM core satellite (currently scheduled for 2013). The **post-launch phase** runs from the launch date of the core satellite until NOAA takes it over from NASA (5 years after launch, in approximately 2018). The potential **NOAA takeover phase** runs from NOAA takeover of the core satellite until its instruments fail or fuel is depleted. NOAA may operate the GPM core satellite during this third phase

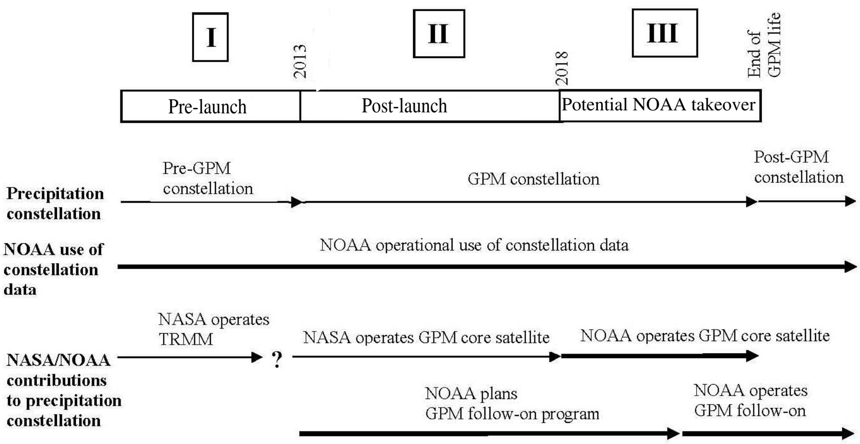

FIGURE 1.3 The three phases of GPM and how they relate to the broader context of NOAA and NASA activities and to the constellation of satellites that already contribute to global precipitation estimates. Time advances from left to right. Thick arrows indicate periods of NOAA involvement.

(Dittberner, 2006) as well as plan and operate a GPM follow-on mission that overlaps with the GPM core satellite. As of the publication of this report, the design specifications could change to allow more fuel to be carried on the core satellite for the possibility of a longer mission. As shown in Figure 1.3, there are roles for NASA and NOAA in all three phases of the GPM mission. The concept of a strategic plan for NOAA's involvement in GPM (Chapter 5) is organized around this same three-phase framework.

GPM AS A PROTOTYPE FOR THE GLOBAL EARTH OBSERVATION SYSTEM OF SYSTEMS

GPM is conceived as a prototype for the emerging Global Earth Observation System of Systems (GEOSS) (Hou, 2005). GEOSS is an international initiative (Box 1.3) aimed at integrating information from numerous Earth-observing systems to improve understanding of processes and linkages and, in turn, enable the public, private sector, and governments to make more informed decisions across a broad spectrum of natural systems. Space-based observations are the backbone of GEOSS (Lautenbacher, 2006).

To achieve an integrated information-based system that meets the societal objectives of GEOSS, satellites systems such as GPM are needed to provide observations with adequate temporal and spatial resolution covering Earth.

BOX 1.3
The Global Earth Observation System of Systems (GEOSS) Partnership

In response to the need for improved access to environmental information, more than 60 countries have endorsed a 10-year plan to develop and implement GEOSS. Nearly 40 international organizations also support the plans. GEOSS has identified nine societal benefit categories in which an integrated and coordinated system of Earth-observing networks would provide help. These categories are disasters, health, energy, climate, water, weather, ecosystems, agriculture, and biodiversity.

Commenting in 2005 on the 10-year strategic plan for the U.S. component of GEOSS, John Marburger, director of the White House Office of Science and Technology Policy and presidential science adviser, stated:

> GEOSS will allow scientists and policy makers in many different countries to design, implement and operate integrated Earth-observing systems in a compatible, value-enhancing way. It will link existing satellites, buoys, weather stations, and other observing instruments that are already demonstrating value around the globe and support the development of new observational capabilities where required.

SOURCE: NSTC, 2005.

SUMMARY

The GPM mission has four functional components (the core satellite, the constellation satellites, the precipitation processing system, and the international ground validation program) that are the result of an international, collaborative effort to expand capabilities for global, space-based precipitation measurements. GPM activities at NOAA and NASA will occur over the three phases of the mission: the pre-launch phase, the post-launch phase, and the potential NOAA-takeover phase. The GPM mission is a prototype for the international GEOSS initiative, which will require an integrated, intercalibration system for space-based instruments. The following chapters provide a framework for NOAA activities—both within the agency and with agency partners—during the three phases of the GPM mission.

2

Lessons from TRMM Applicable to the GPM Mission

The Tropical Rainfall Measuring Mission (TRMM) has provided important lessons that are relevant to the observational and research aspects of the Global Precipitation Measurement (GPM) mission. Much was also learned from TRMM that is relevant to the operational use of GPM data and to an effective partnership between the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA). This chapter addresses the first question of the committee's task: *What lessons were learned from the TRMM mission with respect to operational uses of the data and how can these lessons enhance the use of GPM mission data and other NASA research mission data in NOAA operational forecasts?*

As context to discussing the lessons learned from TRMM, it is useful to contrast the different initial conditions when TRMM was launched in 1997 from those conditions when the GPM core satellite is launched (proposed for 2013 as of publication) (Table 2.1). The difference in the conditions for these precipitation satellites reflects to some extent the lessons that were learned from TRMM. Before discussing the two areas of lessons that directly address the committee's first task, this chapter includes a set of related, but general lessons for space-based precipitation measurement.

LESSONS FOR SPACE-BASED MEASUREMENT OF PRECIPITATION

The overarching technological achievement of TRMM was its demonstration that the mission approach to inferring precipitation from space was sound. TRMM's scientific accomplishments establish its unique role as a "flying rain

TABLE 2.1 Differences in the Context for Launch of TRMM Versus the GPM Core Satellite

Context for Launch of TRMM	Context for Launch of the GPM Core Satellite
Experimental sensors on board (the first deployment of quantitative weather radar in space), including multiple sensors on one spacecraft (e.g., precipitation radar and passive microwave imager).	Proven sensor technology; potential for the GPM dual-frequency precipitation radar to fly with other radars still in orbit (TRMM, CloudSat).
No long data sets to which sensor data could be attached.	Decade-long record of precipitation radar and other TRMM data.
No operational experience with data.	Operational experience with data since 1998.
NOAA scientist involvement in NASA's 1986 workshop on TRMM, and NOAA scientist participation on the TRMM science team. However, there was no expectation (and therefore no planned activities) of operational application of TRMM data at NOAA.	Collaboration among NASA and operational agencies since 2001. NOAA involvement through attendance at annual GPM planning workshops, input on operational requirements for GPM, and participation on the Precipitation Measurement Missions science team. The GPM research plan has operational objectives, and efforts are under way to establish an effective NASA-NOAA partnership for the GPM post-launch phase.
The TRMM ground validation approach followed the traditional lines of rain rate-oriented intercomparisons with classical ground validation site set-ups.	The GPM ground validation program will include quantitative assessment of the distribution and the nature of retrieval errors.
Moist physics in operational models was not well developed.	Moist physics is evolving away from purely parameterized physics toward more explicitly resolved physics in the form of cloud-resolving models. This evolution is removing the artificial distinction between clouds and precipitation.
Data assimilation of moist physics was in its infancy.	Data assimilation of moist physics, while still in its formative stages, is progressing, and will help treat observations of clouds and precipitation as part of one combined system.
Diverse and active community of researchers experimenting with a wide variety of evolving algorithms for retrieving rainfall and related information from passive microwave radiometers.	Dedicated funding and available human resources have diminished.

gauge" and are detailed in reports by the National Research Council (NRC, 2004) and NASA (Adler et al., 2005). The committee identified eight lessons learned from TRMM with respect to space-based measurements of precipitation.

1. TRMM Was a Model for International Cooperation in Pursuing an Earth Remote-Sensing Initiative

TRMM is a bilateral cooperative project between NASA and the Japan Aerospace Exploration Agency (JAXA). The project constitutes a significant investment by both agencies. JAXA contributed the precipitation radar to the satellite and provided the integration and launch aboard the Japanese H-II launcher in 1997. In addition, JAXA collected and preprocessed the precipitation radar data. NASA contributed the spacecraft bus and the remaining sensors. It also contributed integration of the instruments with the TRMM spacecraft and all shipping and handling of the completed spacecraft.

Both countries maintain their own data downlinks and processing systems, but they share data and results. For example, "NASA and NASDA [JAXA's precursor, the National Space Development Agency of Japan] shall share all TRMM data and make such data available to other users for research, operations and other uses under the terms of the IEOS DEP [International Earth Observation System Data Exchange Principles] (contained in the Appendix to this MOU [memorandum of understanding]). The shared data shall include all products from the NASA-provided instruments, the NASDA-provided instrument, and ground truth data used to validate the TRMM products" (NASA, 1995). In addition to NASA and NASDA, the IEOS included the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), NOAA, the Japanese Science and Technology Agency (STA), the Ministry of International Trade and Industry of Japan (MITI), the Japan Environment Agency (JEA), the Japan Meteorological Agency (JMA), and the Canadian Space Agency (CSA). In addition to the partnership on data collection, the mission contributed to the U.S. Global Change Research Program and to related international efforts.

Precipitation measurement from space is an area of great international collaborative potential. The lessons learned from the TRMM bilateral cooperation can be applied in establishing effective international partnerships on GPM and, ultimately, to the transition of GPM from a research mission to a viable operational system.

2. Robustness and High Endurance of the TRMM Microwave Imager and Precipitation Radar Systems in Space

TRMM was designed as a minimum 3-year research mission with a goal of 5 years' duration. The precipitation sensors have now been operating for more than 8 years, and continue to function as designed (Adler et al., 2005). An independent technical assessment of the impact of extended life on spacecraft systems by the Goddard Space Flight Center (Adler et al., 2005) indicated that the "change in risk is minimal." There is a high probability of each of TRMM's four instruments operating successfully for another 5 years from the date of the assessment (Adler et al., 2005). As an example, the robustness of TRMM's measurements has lead to a benchmark 7-year rain climatology, narrowing considerably the range of uncertainty in previous space-based rainfall estimates (Adler et al., 2003; Nesbitt et al., 2004).

3. Value of Precipitation Radar for Observing the Fine-Scale, Three-Dimensional Structure of Precipitation Systems from Space

Discriminating precipitating scenes from cloudy scenes and estimating precipitation over land surfaces are two of the challenges of using passive microwave observations. Precipitation radar provides a more direct observation of precipitation in both cases and provides a far more detailed and potentially accurate measurement of precipitation than is obtained from passive microwave (and visible or infrared) data. Precipitation radar observations have revealed the fine-scale, three-dimensional structure of tropical storm systems (e.g., Nesbitt et al., 2000; Kelley et al., 2004) and provided new insights into the microphysical dynamics of the formation of precipitation (Schumacher and Houze, 2003; Schumacher et al., 2004; Chandrasekar et al., 2005) and the vertical profile of latent heat release (Olson et al., 1999; Tao et al., 2004). The precipitation radar has also exposed issues relating to passive microwave and visible-infrared methods of inferring precipitation and how the accuracy of these methods varies with atmospheric conditions and the space and time scales of interest (Berg et al., 2006). As an example of a rainfall-related feature not previously well-described and understood before TRMM, the TRMM precipitation radar has enabled the quantification of the diurnal cycle of precipitation and the convective intensity over land and oceans in the tropics (e.g., Sorooshian et al., 2002; Nesbitt and Zipser, 2003; Hong et al., 2005).

TRMM's single-frequency precipitation radar (13.8 GHz) represented a significant advance in observation technology. However, due to sensitivity limitations, the TRMM precipitation radar can only detect moderate to high rainfall rates. The major scientific and technological leap forward with the GPM mission is the dual-frequency precipitation radar in the core satellite, which will have several advantages over the TRMM precipitation radar. The two frequencies of the GPM precipitation radar are the "Ku band" frequency (13.6 GHz; similar to the 13.8 GHz frequency of TRMM's precipitation radar) and the "Ka band" frequency (35.55 GHz); the Ka-band frequency has greater sensitivity to low precipitation rates (light rain, drizzle) and snow, and therefore will be able to measure lower rain rates than TRMM. In addition, both frequencies on the GPM core satellite in principle can be used to more accurately estimate precipitation types and rates than with a single-frequency precipitation radar. Research still remains to be performed on both the microphysical inferences and improved precipitation retrieval using spaceborne dual-frequency techniques. The dual-frequency precipitation radar offers excellent potential for inferring precipitation microphysics (Chandrasekar et al., 2003a). The challenges in microphysical inferences and application to precipitation retrieval algorithms are discussed in papers by Chandrasekar et al. (2003b), Iguchi (2006), and Meneghini et al. (1992).

4. Feasibility of Co-located, High-Grade Precipitation Measurements from Space

TRMM has provided important lessons on the optimal approach to measuring precipitation from space (e.g., Adler et al., 2003; Nesbitt et al., 2004). The accurate, scientifically robust measurement of precipitation from multiple sensors on a single platform (e.g., co-located precipitation radar and passive microwave radiometer) has yielded insight into the limitations of different methods and how to improve them (e.g., Berg et al., 2006).

5. Value of a Multi-Sensor Reference Satellite for Calibration of Data from Other Space-Based Observational Systems

TRMM has two unique attributes that make it an ideal “flying rain gauge” for cross-calibrating passive microwave data from other satellites: its suite of complementary sensors and its low, non-sun-synchronous orbit that permits high-spatial resolution measurements. Co-location of the precipitation radar, the microwave imager, and the visible-infrared sensor on TRMM allows the use of high-precision precipitation radar measurements to calibrate radiometric measurements made by the TRMM Microwave Imager (Adler et al., 2003; Nesbitt et al., 2004). Subsequently, the non-sun-synchronous orbit provides orbital intersections between 35 degrees latitude North and South for intercalibration between the TRMM Microwave Imager and other passive microwave measurements from polar-orbiting satellites. For example, TRMM data are used to calibrate rain estimates from other satellites to provide analyses at higher time resolution than available from any single satellite (Adler et al., 2000).

With the co-location of the precipitation radar and the GPM Microwave Imager on the GPM core satellite, the GPM mission will also realize these benefits demonstrated by TRMM. Despite the uncertain status of other satellites in orbit or under development (see Chapter 3), the combination of the precipitation radar and the GPM Microwave Imager will provide a unique reference tool for intercalibration of other microwave imagers and thus enable better products from other microwave imagers.

6. Direct Validation of TRMM Precipitation Measurements Proved Difficult

A comprehensive ground validation program encompasses four major elements: (1) reliable determination of precipitation from ground-based observations on time and space scales compatible with the satellite retrievals that are to be evaluated; (2) broad statistical comparisons of the ground-based observations and retrievals; (3) determination of the specific sources of retrieval errors, in terms of the physical and dynamical aspects of the precipitation environment; and (4) quantitative characterization of the distribution of retrieval errors as a function of meteorological conditions.

Among the many notable aspects of TRMM was the application of substantial project resources to a ground validation program (NASA, 1988, Chapter 7). The stated goal of this pioneering effort was "to provide rainfall measurements which will allow the validity of the TRMM measurements to be established within specific limits" (NASA, 1988). The validation sites were selected to represent the different tropical rainfall regimes.

Broadly speaking, the TRMM ground validation program was designed to focus primarily on the first two elements of a comprehensive ground validation effort. For example, the various observational sites were designed primarily to provide information on the typical retrieval bias for each of the major precipitation regimes of the tropics. While the program provided useful data for "placing bounds" on the acceptability of the TRMM retrievals (NASA, 1988), it generated a limited amount of information about the specific physical sources of retrieval errors and the distribution of errors—information that is important when using the retrievals in an operational setting.

In light of the experience and insight gained from the TRMM ground validation program, GPM has developed a broad strategy for investigating and quantitatively assessing the distribution as well as the nature of retrieval errors. Bidwell et al. (2004) list two fundamental requirements of the GPM ground validation program. The first is to characterize the retrieval errors. The second is continued improvement of the retrieval algorithms. In addition, Bidwell et al. list the following as objectives of the GPM ground validation program:

1. Quantitatively assess the error in spaceborne precipitation retrievals. This includes plans for estimating both the systematic and the random components of retrieval error and characterizing the spatial and temporal structure of the error.
2. Diagnose the sources of error. Since the measurements extend beyond the tropics, GPM algorithms will experience new or modified sources of potential error (e.g., different distributions of precipitation types [stratiform, convective,

lighter rain rate, snowfall], different land-surface conditions and geographical effects, and large-scale forcing.

3. Quantitatively evaluate and improve the retrieval algorithms. Plans for this aspect of the ground validation program include the active participation of algorithm developers.

Advances in the understanding of precipitation physics are vital for satellite algorithm and data product improvements. Recognizing this need, GPM validation plans include both satellite products and cloud-resolving models run at some validation sites (Kummerow, 2006).

Finally, the GPM validation strategy includes documentation of the percentage of time that an algorithm model meets specific accuracy levels for different observed meteorological conditions (Kummerow, 2006). This information is viewed as a first step in diagnosing, understanding, and improving precipitation products as well as numerical models. Further details of the GPM ground validation strategy are included in Chapter 1 ("The International Ground Validation Program") and Chapter 4 ("Ground Validation Support").

7. Feasibility of Obtaining Near-Real-Time Global Coverage of Precipitation Observations from Space

The TRMM satellite was designed to sample precipitation between 35 degrees latitude North and South with sufficient frequency to provide accurate monthly rainfall estimates for five-by-five-degree latitude-longitude boxes. In doing so, TRMM also provided lessons about the optimum approach for obtaining time series of global precipitation measurements from space at higher spatial and temporal resolution. Specifically, TRMM has demonstrated that a satellite with a similar instrument compliment (precipitation radar, microwave imager, visible-infrared sensor) in a non-sun-synchronous orbit can serve as a reference system for calibrating passive microwave and visible-infrared observations from a constellation of other satellites. This approach to obtaining global precipitation measurements has been a focus of considerable applications research (e.g., Joyce et al., 2004; Huffman et al., 2005). These studies have demonstrated the utility of this approach when applied to the intercalibration of the existing constellation of operational and research satellites. NOAA's Climate Prediction Center morphing technique (CMORPH) described by Joyce et al. (2004) is being used routinely to produce NOAA global precipitation analyses (Janowiak and Kousky, 2005). The TRMM multisatellite precipitation analysis at NASA (Huffman et al., 2005) also runs in real-time with results available from the TRMM web site[1] —not a re-

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[1] *http://trmm.gsfc.nasa.gov*.

quired function, but an activity to benefit users nonetheless. A research version of the 3-hour resolution of the multisatellite precipitation analysis is a standard TRMM product (3B42). The database now spans 8 years and forms a base for testing applications. Similar multisatellite-sensor precipitation techniques are being run in near real time by several other groups both in the United States and abroad.

8. Unexpected Bonuses Often Accrue from a Scientific Mission

As with all scientific missions, there is the possibility of accruing additional, unexpected scientific results other than those for which the mission is designed. For example, TRMM achievements have surpassed mission goals in several ways. The scientific goals of TRMM were focused primarily on issues of climate and large-scale climate variability of tropical precipitation (e.g., the El Niño-Southern Oscillation cycle; NASA, 1988). However, TRMM data have also been fundamental for studying a broader and unanticipated range of topics. Such topics include better characterization and understanding of the nature and variability of tropical cyclones (NRC, 2004) and the value of TRMM data when used with coincident observations of other atmospheric parameters. The investigations of human impacts on precipitation by Rosenfeld (1999, 2000) demonstrate the benefits of coincident observations of cloud properties and precipitation, for example. In these studies, cloud microphysical information matched to TRMM precipitation observations provided new and unanticipated insights into the influence of aerosols on the formation or suppression of precipitation.

LESSONS FOR OPERATIONAL APPLICATION OF RESEARCH MISSION DATA

TRMM was planned as a purely research mission with no specific goals for operations, and this has affected the pace and nature of the subsequent development of operational applications of the data. The committee has identified four lessons from TRMM relating to the early operational use of GPM research data and the transition from GPM research to operations. Many of these lessons relate to past differences between research and operational missions.

1. TRMM Planning Did Not Anticipate the Broad Scope and High Degree of Interest That Developed for the Application of TRMM Data in Real-Time Operations

Because TRMM was designed as a research mission, the timely availability of TRMM data was not a significant consideration in the initial planning for the mission. There was no strong motivation for making the TRMM Microwave

Imager data available to satisfy real-time applications and requirements. The precipitation radar data were not made available for a year after TRMM's launch.

2. Application of TRMM Data to Operations Could Have Benefited from More Extensive Pre-launch Planning Within Operational Agencies

The lack of pre-launch planning and budgeting by U.S. operational agencies for mission-oriented application of TRMM data influenced the nature and pace of applications. This was largely a consequence of TRMM planning not including specific application goals and having only limited involvement of operational personnel. With little if any planning prior to launch, it was, in effect, largely left to individual operational centers to recognize and respond to opportunities for near-real-time application of TRMM data.

Many factors probably influenced the decision to invest human and financial resources in developing TRMM applications. These included data availability, ease of application, availability of needed resources, and the likelihood of a significant payoff. For example, since the assimilation of TRMM Microwave Imager precipitation retrievals into the global numerical weather prediction model at NOAA's National Centers for Environmental Prediction resulted in only a small positive impact on the forecasts (Lord, 2004), there was no strong impetus to exploit the TRMM observations. Conversely, the United States has led the way in many applications where use of the TRMM data was straightforward, and the payoff clear, notably the extensive use of TRMM Microwave Imager and Precipitation Radar data for tropical cyclone monitoring (Chapter 3) and the use of TRMM Microwave Imager data for sea-surface temperature mapping.

As mentioned in Table 2.1, rainfall data assimilation was in its infancy at the time TRMM was launched. As a consequence, this limited the effective use of TRMM data in numerical weather prediction. However, TRMM has generated the momentum for improving data assimilation systems and numerical weather prediction models, which may better prepare operational agencies for the launch of the GPM core satellite.

The ultimate limiting factor in what can be achieved both operationally and for research with GPM may well not be hardware but rather human resources, which in turn depend on funding to government research centers as well as to partners in academic institutions.

3. TRMM Has Provided Important Lessons Relating to the Pace of Operational Application of Various Types of Research Data

Since the operational community was already using passive microwave data from operational satellites, there was an early eagerness to apply the TRMM Microwave Imager data. In contrast, the operational community (both inside and outside the area of numerical weather prediction) has been much slower in exploiting the new precipitation radar data in part due to the small swath width (200 km), which limits utility of the precipitation radar data. This may also be due, at least in part, to lack of specific operational research and development plans for exploiting these data. Eight years after launch of TRMM, precipitation radar data are still used primarily by the research community and are still underutilized in operational applications. The lesson from TRMM is that digesting new types of data and applying them in operational contexts can take a significant amount of planning, time, and resources.

4. Uncertainties About TRMM's Future Beyond Its NASA-Funded Research Mission Caused the Operational Modeling Community to Delay Allocating Resources to Fully Exploit the TRMM Data

TRMM demonstrated that uncertainties about the future of a research mission can affect the pace and degree of operational use of the data. TRMM was initially funded as a minimum 3-year research mission with a goal of 5 years' duration, without assurance of continuation beyond the research phase. This affected decisions to apply precipitation radar data to improve model physics and data assimilation procedures needed to fully exploit TRMM observations (NRC, 2004). There was generally little impetus to invest scarce operational resources to develop tools needed to exploit the research data.

FINDING AND RECOMMENDATION TO APPLY THE LESSONS FROM TRMM TO ENHANCE THE OPERATIONAL USE OF GPM MISSION DATA

The scientific and programmatic lessons learned from TRMM have fundamentally influenced the design of the GPM mission and NOAA planning for operational use of the GPM data. For example, because the pace of operational application of research data can be significantly enhanced if the mission has well-defined application goals, GPM has integrated application goals in addition to its scientific objectives. In addition, the GPM observational system is designed to be a prototype pre-operational research mission with commensurate scientific and technical requirements (Hou, 2005).

To fulfill the broad application goals of the GPM mission as well as to satisfy NOAA requirements for real-time applications, the GPM data will have to be available for operational use in a more timely manner than was the case for the TRMM data (White, 2005). The reductions in data latency planned for GPM will broaden the range of potential operational applications.

Recognizing that operational application of TRMM data could have benefited from participation of operational personnel in the implementation of mission application goals, NOAA has involved personnel in a number of GPM preparatory activities (see Chapter 4). The planning for a close partnership between

NASA and NOAA to support the post-launch phase of GPM and facilitate early NOAA operational use of GPM data represents another fundamental difference from TRMM.

The operational application of TRMM data could also have benefited from pre-launch planning within operational agencies. It is important that NOAA develop and budget for comprehensive, coordinated, agency-wide preparatory activities prior to the post-launch phase of GPM to facilitate early and efficient exploitation of the data. Without comprehensive pre-launch planning, NOAA applications run the risk of being a collection of individual, ad hoc targets of opportunity—a situation similar to the early stages of TRMM—rather than a coherent, adequately funded agency effort that addresses the needs of the many NOAA centers that require space-based precipitation data. NOAA's pre-launch planning would have to be aligned with and integrated into the basic structure of NOAA activities and make full use of the existing constellation of passive microwave satellites and the combination of the TRMM Precipitation Radar and the TRMM Microwave Imager.

To avoid the potential negative effects on operational use of GPM data due to uncertainty regarding NASA's continuation of the GPM mission, NOAA will have to plan early. This will involve NOAA-NASA long-term operational and budget planning for the transition of GPM from a research mission to an operational system. NOAA is not currently budgeted to take over any NASA satellite during the GPM research mission. However, NOAA is interested in taking over NASA-launched satellites that are a part of a long, continuous series designed for long-term measurements of parameters that NOAA needs (Dittberner, 2005). Since the NOAA takeover of a NASA satellite must be planned many years in advance, it is important that NOAA and NASA begin working together in earnest to determine agency roles and responsibilities beyond the post-launch phase of GPM. Based on its analysis, the committee offers the following finding and recommendation:

> *Finding:* **Operational application of research data can be hampered if the mission has no specific application goals, no pre-launch planning for operational exploitation of the data, and uncertainty regarding the post-research phase. Lessons learned from the absence of such planning for TRMM have stimulated informal pre-launch planning by NOAA for operational exploitation of GPM data, and NOAA has expressed interest in the concept of operating the GPM mission after the NASA phase.**

> *Recommendation 2.1:* **As soon as possible, NOAA should formalize its GPM planning by developing a comprehensive, coordinated, agency-wide strategic plan for activities in all three phases of the GPM mission. In addition, NOAA and NASA should determine their respective roles and responsibilities in all three phases.**

A long-term, strategic program of applied research will address many complex problems regarding NOAA's use of space-based precipitation information to improve modeling, forecasting, and climate applications. To guide NOAA's efforts in developing a GPM strategic plan, the following chapters identify operational uses for GPM data and recommend preparation activities.

3

Precipitation Data in NOAA Operations

This chapter describes the needs, capabilities, and potential opportunities of the National Oceanic and Atmospheric Administration (NOAA) for using space-based precipitation estimates. To identify the best uses of Global Precipitation Measurement (GPM) mission data at NOAA, the committee first examines NOAA mission requirements for precipitation data and related products. Next, the committee identifies current sources of NOAA operational precipitation data and recommends improvements for these sources in preparation for GPM. Next, five challenges are identified for future space-based precipitation missions. Finally, this chapter outlines the applications of space-based precipitation data in general and the potential applications of GPM mission data specifically.

NOAA MISSION REQUIREMENTS FOR PRECIPITATION DATA AND RELATED PRODUCTS

Global observation of precipitation on a range of time and space scales is essential to achieving NOAA's mission objectives related to the monitoring and prediction of weather, climate monitoring, many aspects of hydrologic monitoring and prediction, climate data set development, and more (Box 3.1). NOAA maintains or contributes to a wide variety of in situ and satellite-based precipitation measurement systems in support of its mission and the World Meteorological Organization (WMO) World Weather Watch. Because precipitation cross-cuts many applications, NOAA's production, application, dissemination, and archiving activities associated with precipitation data are carried out at multiple centers. NOAA requirements for precipitation data were reviewed at a 2001

BOX 3.1
NOAA's Five Primary Mission Goals

1. Protect, restore, and manage the use of coastal and ocean resources through an ecosystem approach to management.
2. Understand climate variability and change to enhance society's ability to plan and respond.
3. Serve society's need for weather and water information.
4. Support the Nation's commerce with information for safe, efficient, and environmentally sound transportation.
5. Provide critical support for NOAA's mission.

SOURCE: NOAA, 2004.

workshop (NOAA, 2002), and these requirements are discussed in more detail in the following sections.

Requirements for Weather Applications

The critical requirement for weather-related applications is timely and continuous availability of accurate precipitation data transmitted in WMO formats. NOAA weather-related activities requiring precipitation data include nowcasting (0-3 hours lead time); short-term forecasting (3-12 hours), multiday numerical weather prediction (NWP) forecasts, and preparation and dissemination of centralized forecast guidance.

Many of NOAA's weather-related (and climate-related) operational activities are centered in the National Centers for Environmental Prediction (NCEP). NCEP's operational needs for global precipitation data include initialization of atmospheric and surface hydrologic (soil moisture) components of coupled NWP models and forecast verification. NCEP's Environmental Modeling Center needs data describing precipitation characteristics, processes (e.g., phase, type, vertical distribution), and ambient conditions (e.g., temperature, humidity, winds) for improving model physics and data assimilation methodology. NCEP central operations provide services in the form of centralized forecast guidance and analysis products that support the public use of NCEP's National Weather Service (NWS) forecasts. These products, which include precipitation forecasts, are delivered through the NCEP Hydrometeorological Prediction Center (heavy precipitation forecasts), Storm Prediction Center (severe weather forecasts), Tropical Prediction Center (tropical cyclone forecasts), and Aviation Weather Center. Frequent sampling and timely data availability are also critical for precipitation nowcasts and short-term projections prepared by the National Environmental Satellite, Data, and Information Service (NESDIS) Satellite Analysis Branch.

Requirements for Climate Applications

NOAA's climate-related requirements for precipitation data are similar to requirements for weather-related activities with three exceptions: (1) the requirements for timely receipt of precipitation data for operational purposes are generally less stringent, (2) there are more stringent requirements for absolute accuracy, and (3) there is a fundamental need for long, stable, and consistent precipitation time series. NOAA climate-related operational activities require precipitation data for monitoring, diagnosis, and prediction of short-term (seasonal to interannual) climate variability. Precipitation data are also required for climate data set development and for mission-oriented research on climate variability, diagnosis of climate trends, and modeling of climate change.

The NCEP Climate Prediction Center provides near-real-time monitoring, assessment, and projections of seasonal-interannual climate variability for use by U.S. agencies with national and international interests, United Nations agencies (Food and Agricultural Organization, WMO), and the public. The Climate Prediction Center's satellite-based, high-resolution morphing technique (CMORPH) for global precipitation analysis is a key tool for supporting the Climate Prediction Center's monitoring and diagnostic activities.

The NOAA Climate Diagnostic Center requires precipitation data to support its mission of providing diagnostic information on the nature and causes of climate variations, with the goal of predicting these variations.

The NOAA Climate Program Office is a focal point for many climate activities within NOAA. The Climate Program Office supports several projects dealing with the development and use of satellite precipitation data sets. These projects include the Climate Change and Detection Project, the Applied Research Center for Data Set Development for transition of Climate Change and Detection Data Projects to NOAA operations, and the Scientific Data Stewardship Program, which governs the production of climate data records.

Requirements for Hydrologic Applications

Surface hydrology requirements for precipitation data intersect weather and climate needs. They include flash flood forecasts and warnings, monitoring and assessing the impact of drought (e.g., fire risks, crop yields, river stage forecasts), monitoring and predicting runoff from the snow pack in the western United States (which is of paramount importance for water resource management), and other hydrologic information from NOAA's 13 River Forecast Centers.

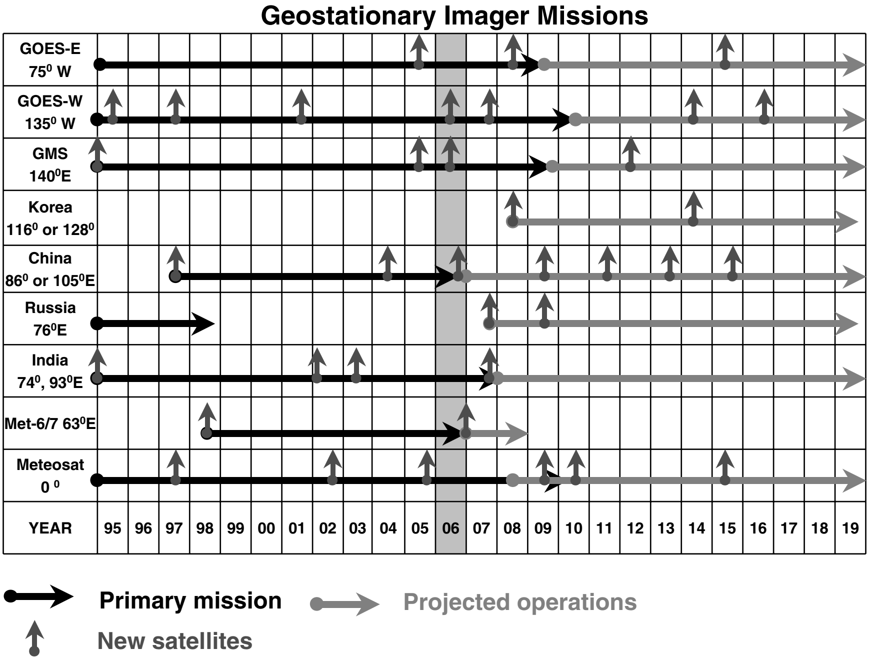

FIGURE 3.1 Duration of spaceborne, geosynchronous imager missions and their potential extensions (explanations of program name abbreviations are found in the "Visible and Infrared" section later in this chapter). Future missions are subject to change.

NOAA's Ability to Fulfill Its Precipitation Measurement Requirements

Increasingly comprehensive and higher-quality satellite precipitation data and data products have become available during the past several years as a consequence of the launch of the Tropical Rainfall Measuring Mission (TRMM) and a number of polar-orbiting satellites carrying passive microwave sensors. Despite these advances, NOAA's requirements for global precipitation data continue to exceed what is available (NOAA, 2002), and each of the primary sources of space-based precipitation information has different strengths and weaknesses (see Figure 1.2 and Figure 3.1) with respect to fulfilling these data needs. At NOAA's precipitation workshop in 2001, participants identified NOAA's requirements that would not be met by existing or planned systems (NOAA, 2002). The deficiencies in space-based observations that were identified can be summarized into three broad categories:

1. data quality and consistency and quantitative description of error characteristics,

2. time and space resolution, and
3. timely availability for operational use.

Participants reached the conclusion that to mitigate the deficiencies noted in their report, "substantial improvements in this information are necessary to advance beyond our present capabilities" (NOAA, 2002). Some of the deficiencies have now been mitigated (e.g., higher-resolution global analyses have been developed [in prototype] by combining information from polar-orbiting passive microwave and geosynchronous infrared observations [see Figure 1.2 and Figure 3.1]), but for the most part the deficiencies still exist. The workshop report recognized that many of the existing deficiencies can be significantly mitigated by GPM (see NOAA, 2002, Finding 6 and Recommendation 1). Finding 6 in the workshop report states: "The proposed NASA/Global Precipitation Mission would provide data that would greatly improve NOAA's ability to monitor and predict weather and climate variability" (NOAA, 2002). Recommendation 1 states: "NOAA should become an active partner with NASA [National Aeronautics and Space Administration] in the Global Precipitation Mission. This system will provide the global three hourly precipitation estimates required by the operational modeling centers. Furthermore, significant improvements in precipitation information for nowcasting, extreme precipitation events, and flash floods will be achieved when geostationary data, gauges, and radars are combined with GPM. Consideration should be given to the establishment of a science team or working group that would define NOAA's role in and relationship to GPM" (NOAA, 2002).

SOURCES OF NOAA OPERATIONAL PRECIPITATION DATA

There are two primary sources of operational precipitation data: ground-based observation systems and space-based observation systems. As the GPM core and constellation satellites supplement these sources, they will benefit from being validated against data from a robust ground-based network. This section reviews the status and attributes of ground-based and satellite sources and makes recommendations for improvements that will benefit GPM in particular and global precipitation estimation in general.

Ground-Based Sources

The continental United States is instrumented with a variety of rain gauges and weather radars that measure precipitation. Both sources have a variety of spatial and temporal sampling approaches that depend on domain and precipitation type.

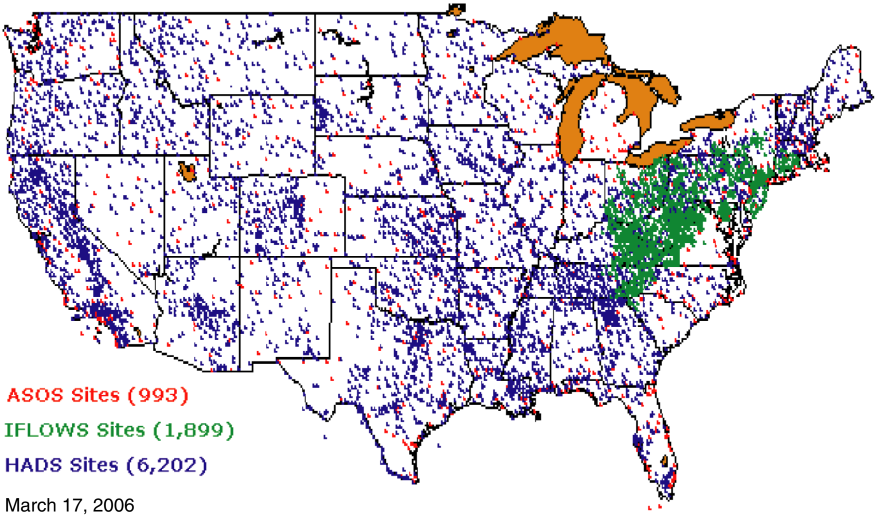

FIGURE 3.2 Distribution of rain gauge data available to NOAA in near real time from three networks: ASOS sites (red), IFLOWS (green), and HADS sites (blue). SOURCE: NWS, 2006a,b,c.

Rain Gauge Data

Rain gauge data for NWS operations in the continental United States come from multiple agencies in a cooperative network that combines the physical resources of these agencies and is facilitated by good communication links and automation software. The data from these multiple sources undergo quality control and are incorporated in near real time to form an extensive rainfall database. The data are analyzed to map precipitation distribution, determine the potential extent of flooding, and calibrate and validate radar and satellite precipitation estimates.

The following observation networks contribute to NOAA operations: (1) the automated surface observing system (ASOS), (2) the Integrated Flood Observing and Warning System (IFLOWS), and (3) the Hydrometeorological Automated Data System (HADS) (Figure 3.2). The HADS data set comes from a number of agencies (Table 3.1).

In addition to the three networks mentioned above, data sets from local, state, and federal cooperative efforts, known as "mesonets," are integrated into near-real-time data streams that feed NOAA operations. As additional sensors are connected into these mesonets through upgraded data links and become accessible on the Internet, further opportunities will emerge from multiagency partnerships that tap into mesonets and observing systems.

TABLE 3.1 Rain Gauge Networks in the Hydrometeorological Automated Data System

Agency, Data Set Program	Number of Gauges
Federal, State Wildland Fire	2,400
U.S. Geological Survey	1,836
U.S. Army Corps of Engineers	1,757
NWS	234
Data Collection Service	117

NOTE: HADS data provide near-real-time rainfall accumulation in the continental United States. The distribution of gauges is nonuniform, and the sampling frequency ranges from 1 minute to daily.
SOURCE: NWS, 2006b.

Whereas rain gauge data are extensive in some regions, nonuniform gauge placement (e.g., Figure 3.2) creates sampling problems such as biases (Sevruk, 1989). In addition, rain gauge measurements have inherent inaccuracies that must be addressed before these data can contribute to the overall precipitation mapping mission (Steiner et al., 1999). Rain gauge data are often treated as "surface truth," but comparisons with rainfall estimates from radar and satellite rain estimates remain uneven due to these sampling inconsistencies and inaccuracies.

Finding: **In collaboration with other agencies, NOAA maintains an extensive rain gauge network that provides data in near real time that will contribute to GPM's calibration and validation efforts. The value of this network to such efforts will be enhanced as data links are upgraded and new mesonets and observing systems become more accessible with rigorous quality control.**

Recommendation 3.1: **NOAA should explore collaborative efforts to augment the existing rain gauge network with additional resources coming online through mesonets that are increasingly used by local, state, and federal agencies to quantify precipitation for many near-real-time applications. NOAA should maintain rigorous quality control and integrate the resultant rain gauge data sets into GPM calibration and validation efforts.**

Radar Data

The NWS operates an extensive network of real-time radar (Weather Surveillance Radar 88 Doppler [WSR-88D] Next Generation Radar [NEXRAD])

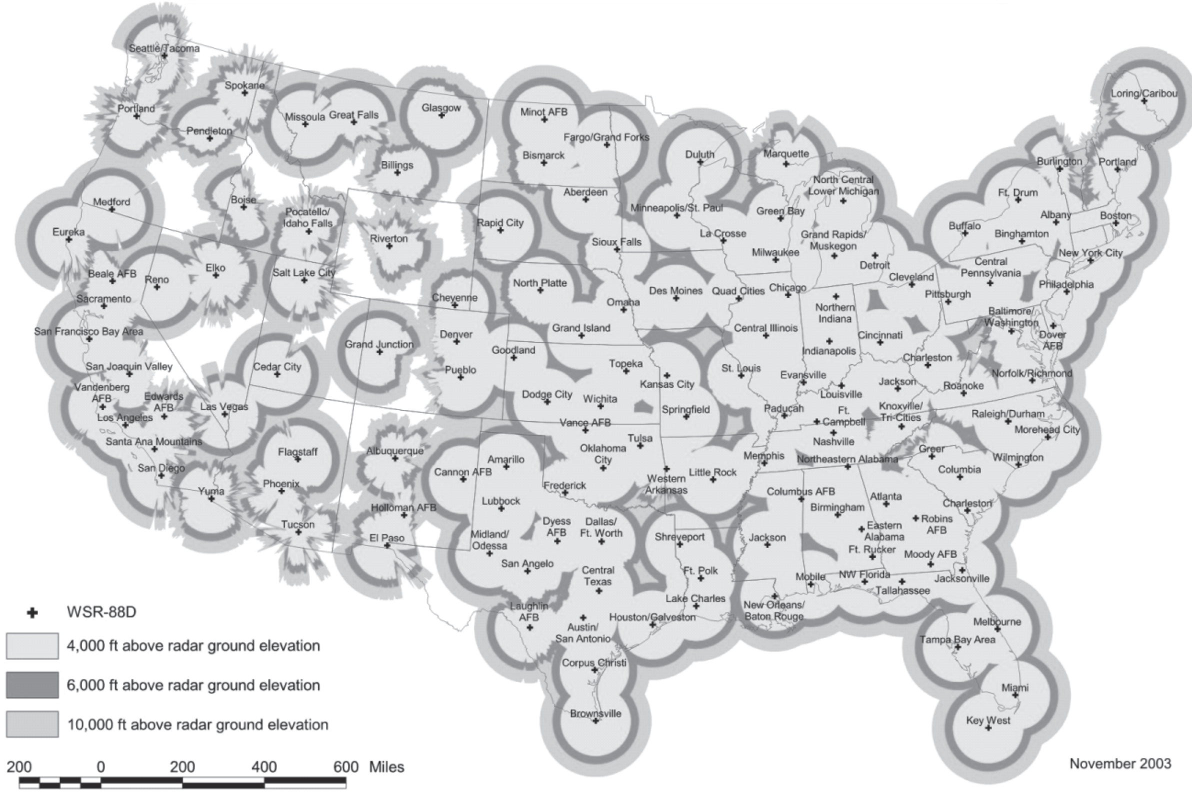

FIGURE 3.3 Location of NOAA WSR-88D NEXRAD radar sites in the continental United States and the distribution of coverage at altitudes of 4,000, 6,000, and 10,000 feet (tan, orange, and blue circles, respectively). SOURCE: NWS, 2006d.

sites (Figure 3.3) around the continental United States, Alaska, Hawaii, Guam, and Puerto Rico that are used in concert with rain gauge data to map precipitation. The NEXRAD network provides near-real-time rain totals (with updates every 6 minutes) that aid in issuing flood watch and warning nowcasts and forecasts. The network's ability to fully automate the retrieval process and quickly communicate the digital values throughout a region and across the continental United States is of particular value to the NWS River Forecasting Centers.

Real-time radar rain estimates are especially good in the eastern two-thirds of the United States, where terrain blockage issues are infrequent (Maddox et al., 2002). Real-time rain measurements permit emergency managers to respond quickly. Combined radar and rain gauge values enable creation of enhanced data sets benefiting multiple user communities (e.g., flood control, agriculture, transportation). NEXRAD data are crucial during rapidly evolving summer thunderstorm events as well as for prolonged and extreme events such as landfalling tropical cyclones.

In addition to the positive attributes of the NEXRAD network, it has some shortcomings due to terrain blockage in mountainous areas (Figure 3.3); inability to capture low-level rain because the radar beam rises with distance from the radar site; lack of uniformity of the reflectivity versus rain rate relationship from

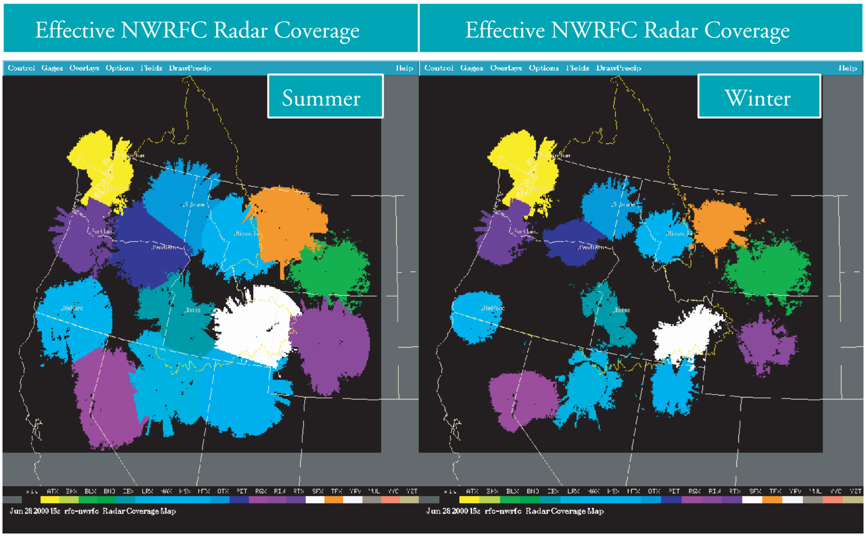

FIGURE 3.4 Change in effective NEXRAD radar coverage in the western continental United States due to wintertime precipitation and high terrain (right panel) compared with summertime coverage (left panel) when convection and associated higher cloud tops enhance the spatial sampling. SOURCE: Kondragunta, 2005.

one location to another and over time; difficulty with mixed-phase and frozen precipitation; decreased wintertime radar coverage in the western United States because low-level precipitation dominates during the winter (Figure 3.4); and data interruptions during extreme events such as hurricanes due to power or communications going offline.

The shortcoming related to interruptions can be reduced by upgrading communications systems and building in greater redundancy. The drawback related to accuracy of rain rate estimates can be mitigated by removing biases via TRMM-like precipitation radars (Anagnostou et al., 2001) and by deploying dual-polarization radar (Bringi and Chandrasekar, 2001; Ryzhkov et al., 2005). In addition, some of the shortcomings of ground-based sources in general will be mitigated by higher-fidelity satellite precipitation estimates.

***Finding:* NWS radar precipitation mapping provides critical real-time monitoring and forecasting capabilities that support many NOAA functions and offices. In addition, this data source will be invaluable to GPM calibration and validation efforts. However, the radar network suffers from a number of shortcomings with respect to accuracy and spatial and temporal coverage that can be ameliorated with radar and power upgrades and increased communications redundancy.**

***Recommendation 3.2:* NWS should proceed with upgrading the NEXRAD network with dual-polarization radar and should enhance network reliability with upgraded power and communication redundancy. NOAA should integrate NEXRAD data sets into GPM calibration and validation efforts.**

Satellite Sources

Satellite sensors mitigate several weaknesses in rain gauge and ground-based radar data sets; thus, the combination of gauge, radar, and satellite precipitation data provides a powerful tool for multiple applications. For example, space-based sensors sample areas where in situ precipitation observations are absent. In addition, they supplement in situ observations in regions where ground-based sites are sparse (most polar-orbiting passive microwave sensors view a swath that spans the equivalent of three to five NEXRAD radar coverages optimally arranged along a satellite path). Furthermore, satellite observations can delineate areas where no precipitation is falling over vast oceanic regions and merged infrared-microwave products have high temporal refresh. Lastly, geostationary imagers can capture data at a rate that is sufficient to monitor vigorous convective activity (imagers view the entire continental United States every 15 to 30 minutes with spatial resolutions of 4 to 8 km at nadir,[1] and when operated in "rapid scan" mode, these imagers capture snapshots [over a smaller spatial domain] as frequently as each minute). NOAA's two major sources of space-based precipitation information are visible and infrared data from geostationary satellites and passive microwave data from polar-orbiting satellites.

Visible and Infrared

Visible and infrared imagery first became available from satellites in the mid 1960s. The approach to inferring precipitation from these observations was initially centered on indirect (or "proxy") techniques that relate visible and/or infrared observations of brightness or temperature of cloud tops to large-scale, time-averaged convective rainfall amounts over the global tropics (Arkin, 1979). Thus, although colder cloud tops imply relatively higher cloud tops and the potential for heavier rainfall, the correlation is often poor and varies considerably with time, location, and precipitation regime (e.g., convective or stratiform). However, the wealth of high-quality (1-4 km nadir spatial resolution) geostationary visible-infrared data and the frequent temporal sampling (15-30 minutes over the continental United States) are key ingredients for precipitation monitoring. Although cloud-top temperatures, cloud-top heights, and cloud type are not highly correlated with instantaneous rain rates, the correlation is strongest for warm-season convective systems that frequent the eastern and midwestern continental United States.

Operational geostationary visible-infrared digital data sets cover the globe between 60 degrees latitude North and South and are routinely available for near-real-time applications. The geostationary constellation is an international collaboration in which very large data sets are exchanged under the auspices of the World Meteorological Organization. This constellation includes Meteosat-8 (Meteorological Satellite 8; 0° E, European Organisation for the Exploitation of Meteorological Satellites [EUMETSAT][2]), Meteosat-5 (63° E, EUMETSAT), INSAT (Indian National Satellite; 74° E, India), FY-2 (Fengyun-2; 105° E, China), MTSAT/GMS-6 (Multi-Functional Transport Satellite/Geostationary Meteorological Satellite; 140° E, Japan Meteorological Agency), GOES-West (Geostationary Operational Environmental Satellite-West; 135° W, United States) and GOES-East (75° W, United States). Figure 3.1 shows geostationary sensors and their data availability since 1995. Due to sensor evolution and specific country preferences, no two sensors are identical with respect to available channels or spatial and temporal sampling.

All geostationary visible-infrared imagers include a minimum of one visible

[1]Directly below.

[2]0° East is the nadir angle of the satellite, and European Organisation for the Exploitation of Meteorological Satellites is the operator.

channel and multiple infrared bands that can be used for identifying clouds, mapping cloud-top temperatures, and in many cases, assisting in determining cloud type using various cloud classification schemes. Most clouds between 60 degrees latitude North and South are resolved throughout the day.

Geostationary sensors have evolved due to each country's efforts to provide sorely needed operational weather and environmental information within its regional domain as noted in Figure 3.1. Note that the current configuration has complete global coverage at the equator and in many cases overlap between consecutive satellite sensors. In addition, spare geostationary sensors from one country have been successfully "loaned" to other WMO members when hardware "glitches" limit sensor availability (EUMETSAT has helped the United States, and the United States has helped Japan). The "health" of the global geostationary constellation is at an all-time high, and this coverage has now reached the level of maturity required for routine "blended" algorithms that combine the best of geostationary visible-infrared and the more infrequent passive microwave imager polar orbiter data sets.

Microwave

The first Special Sensor Microwave/Imager (SSMI) was launched in 1987 as part of the continuing series of operational, polar-orbiting Defense Meteorological Satellite Program (DMSP) satellites operated by the Department of Defense (DOD). The sensor provided the first operational passive microwave data (Hollinger, 1989) for developing and applying more physically based algorithms that draw on direct measurements of the natural irradiative properties of precipitation particles. The temporal sampling of passive microwave data has improved as the DMSP constellation has been supplemented with new satellites (Figure 1.2). Three such satellites are now operational. In addition, the SSMI sensors have been upgraded with the Special Sensor Microwave Imager Sounder (SSMIS), launched in 2003 (Wessel et al., 2004).

The SSMIs have been augmented with research sensors carried on NASA platforms. For example, TRMM provided both the TRMM Microwave Imager and Precipitation Radar, launched in 1997. TRMM was followed by the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) on Aqua in 2002. Both the TRMM Microwave Imager and AMSR-E have rain-sensitive frequencies (Kummerow et al., 2000; Wilheit et al., 2003) and higher spatial resolution for mapping finer-scale rain-causing cloud systems than the SSMI or SSMIS. In 2003, the Navy launched the Coriolis WindSat polarimetric radiometer (Gaiser et al., 2004) as a Conical Scanning Microwave Imager Sounder (CMIS) risk reduction sensor.[3] Although WindSat's primary

[3]That is, in case the CMIS sensors on board National Polar-orbiting Operational Environmental Satellite System (NPOESS) satellites are delayed or do not launch.

mission is to test wind vector retrieval using microwave radiometry, it has frequencies similar to the TRMM Microwave Imager and AMSR-E for precipitation estimates.

Rain rates can also be retrieved using microwave sounder data in addition to the imager data described above (i.e., SSMI and SSMIS). For example, the Advanced Microwave Sounding Unit B (AMSU-B), which is used operationally to measure atmospheric moisture, also has channels that can extract rain rates across the sensor's 2,300 km swath (Weng et al., 2003). Unfortunately, fluctuations in cross-track resolution make AMSU-B imperfect as a source of microwave rain rate estimates. However, the broad swath and availability of three operational AMSU-B sensors help mitigate these temporal sampling problems. AMSU-B data are now complemented by the Microwave Humidity Sensor (MHS) on board recently launched NOAA-18 and will follow shortly on METOP-1 as noted later.

The CloudSat mission flies the first millimeter-wavelength radar system that observes both clouds and precipitation. CloudSat flies in formation with Aqua, thereby providing a near-simultaneous set of radar observations and passive microwave observations of AMSR-E. Methods to derive precipitation information using this combination of radar and passive microwave observations have been developed and will continue to evolve. CloudSat radar observations are also viewed as an important contribution to the measurement of snowfall, and snow-related research activities are currently being formulated around these new observations (Bennartz and Ferraro, 2005).

Planned Satellite Precipitation and Related Missions That Contribute to the Global Precipitation Constellation

In general, the geostationary constellation health will markedly improve in the next 5 years, while the opposite is true for passive microwave imagers on low-orbiting platforms. Also, microwave sounders will remain on both U.S. and EUMETSAT polar orbiter platforms and provide rainrate data sets. A wealth of geostationary visible-infrared sensors are planned over the next 10 years, as noted in Figure 3.1, that will assist in "blended" precipitation estimates. In addition to new satellites in the GOES, Meteosat, INSAT, FY-2, and GMS series, both Korea and Russia will join the geostationary satellite community with new entries that will provide enhanced data continuity and/or spatial resolution for specific areas now viewed at large viewing angles with existing satellite sensors. Potential issues still remain if specific problems occur with the launch or operations of individual satellites, but the ability to mitigate hardware flareups can be resolved more easily with this overlapping constellation configuration.

It should be noted that all geostationary member satellites are rapidly approaching the inclusion of visible-infrared and water-vapor channels and 10-bit digitization as the standard suite of instruments. These instruments will greatly aid precipitation applications and provide standardization across the globe that will enhance global precipitation continuity.

In addition to plans for the GPM core satellite, a number of complementary missions are planned in the United States and internationally (Figure 1.2) that contribute to the constellation of opportunity needed to maximize the coverage and refresh rate of the GPM mission data retrievals. Such a constellation already exists (Figure 1.2) and even has a core satellite with a precipitation radar instrument (TRMM) and a precipitation-capable radar for measuring snow in higher latitudes and light precipitation (CloudSat). However, these capabilities are short term (scheduled to end operation before the launch of the GPM core satellite), and there is uncertainty surrounding planned missions beyond the end of these missions. It is unclear how the constellation will evolve over the GPM time frame.

The GPM mission is currently slated to include two satellites: (1) the core satellite with dual-frequency precipitation radar and microwave imager sensors, and (2) a free flyer with another microwave imager sensor. Although orbital characteristics are not final, options include a TRMM-like low-latitude inclination that would permit both a continuation of diurnal rainfall monitoring and frequent overpasses for tropical cyclone applications globally. In addition, the low inclination will provide frequent opportunities for cross-calibration of higher-inclination passive microwave sensors (e.g., SSMIS).

Through DMSP, DOD plans to launch four SSMIS sensors over the next 1-7 years. These will lead up to the follow-on microwave imagers onboard the NPOESS sensor suite as DOD and NOAA operations converge under the NPOESS umbrella. The 15-year NPOESS program proposes three microwave imaging sensors in a two-orbit constellation instead of the original six CMIS sensors in a three-orbit configuration. The NPOESS restructuring in June 2006 has deleted the CMIS sensor program in lieu of recompeting this sensor's capabilities for three sensors on spacecraft C2-C4. Thus, without a C1 sensor in the year 2013, the first NPOESS microwave imager (yet to be named) will be no earlier than the C2 launch in 2016.

Although frequencies and sensor attributes are not known at this time, it is highly likely that rain products will be feasible with the three NPOESS microwave sensors. However, the reduction from six to three sensors and the current launch schedule significantly impact the global mix of microwave imagers available for precipitation monitoring. Temporal sampling will be hindered because fewer sensors equate to less frequent observations and imply that enhanced reliance will be placed on "merged or blended" precipitation techniques using both passive microwave and visible-infrared data sets. All options will directly affect the GPM constellation's ability to meet temporal and spatial sampling and accuracy goals.

It should be noted that NPOESS data have potentially greatly enhanced data latency through the "SafetyNet" data relay system (Hoffman, 2006). The vast majority of NPOESS global digital data will be available within 30 minutes versus the current values of 1-4 hours for most polar-orbiting data today.

The rapid data availability bodes well for near-real-time merged precipitation algorithms.

Another potential U.S. contribution to the microwave constellation that is still in the discussion stage is to include a microwave imager on the next generation of operational geostationary sensor suites (GOES-R), although the earliest feasible availability is not likely until around 2020. All but one of the other planned missions discussed in this section are polar-orbiting missions, which share drawbacks of having poor data refresh rates and modest spatial resolution (due to limited antenna size and high satellite altitude). A geostationary imager would improve refresh rates. In addition, the proposed sensor would use higher frequencies than on present systems to partially mitigate spatial resolution issues.

European sensors were added to the microwave constellation with the launch of the MHS—a follow-on to AMSU-B—now operational on board the NOAA-18 satellite. More importantly, MHS is slated for the European Meteorological Operational (METOP) weather satellite series scheduled for first launch in Fall 2006, which will provide key atmospheric moisture data for the next 15 years from METOP 1 to METOP 3. METOP's MHS will provide the midmorning orbital plane in conjunction with the NPOESS microwave imager in the early morning and afternoon orbits. Although METOP will carry a microwave moisture sounder, it will not carry a microwave imager (though future plans may include an imager starting with METOP-4). Another potential European contribution to the constellation is the proposed European Global Precipitation Measurement (EGPM) mission satellite, which would have global coverage and carry a radar in addition to a microwave imager and would target light rainfall and light-to-medium snowfall. Although this is potentially a unique and central contributor to the overall precipitation constellation, the uncertain status of EGPM and the lack of funding mean it cannot be relied on as a contributor to future precipitation measurements.

The French-Indian Megha-Tropique mission carrying the Microwave Analysis and Detection of Rain and Atmosphere Structure (MADRAS) microwave imager is planned for launch in 2008 or 2009. It will occupy a 20-degree tropical inclination (compared with TRMM's 35-degree inclination) and provide coverage of tropical diurnal rain rates. The 20-degree inclination of the MADRAS microwave sensor on board the French-Indian Megha-Tropique mission will provide key temporal coverage not feasible from any other sensor than TRMM's Microwave Imager. In addition, the orbit will provide many intersections with more highly inclined GPM constellation sensors and, thus, opportunities for intersensor calibration and validation. However, many near-real-time applications of data from this spacecraft may be prevented because of the plans for only three downloads per day to a single receiving station. For this sensor to contribute to the global observing system, the satellite community will need to explore options (such as incorporation of a Tracking and Data Relay Satellite System) that can provide this vital tropical sensor data set globally in near real time.

China plans to launch a multichannel Microwave Radiation Imager (MWRI) on board its FY-3A and 3B satellites in 2007 and 2009, respectively—a useful addition to the microwave radiometry efforts (Figure 1.2). China has discussed the option of flying a low-orbit precipitation mission similar in concept to TRMM with both a precipitation radar and a microwave radiometer. In addition, Japan will launch the Global Change Observing Mission (GCOM) by 2012, which combines multiple channels sensitive to rain with superb spatial resolution. This mission follows in the footsteps of the Advanced Earth Observing System program that carried the AMSR-E sensor.

> ***Finding:*** **Availability of the NPOESS microwave imagers in both proposed NPOESS orbits is essential to any precipitation-measuring constellation. Yet there is uncertainty about the NPOESS microwave sensor design. Changes in sensor configuration (i.e., antenna size and/or channels) or launch dates will have immediate impacts (potentially negative) on GPM mission goals (and, consequently, its contribution to GEOSS) unless these changes can be mitigated by other satellites or sensors. Without the NPOESS microwave imaging sensors, only two to five microwave imagers will be flying at any given time in the 2015-2025 period, compared to seven sensors available today (there are still unresolved global access issues for some foreign satellite data sets). These seven sensors mitigate many inherent temporal sampling issues for polar-orbiting satellites.**

> ***Recommendation 3.3:*** **NOAA headquarters should communicate to the NPOESS program office the critical role the NPOESS microwave imagers will play as a linchpin in its GPM efforts and their contribution to GEOSS. In addition, it should communicate the ramifications to GPM and GEOSS of all NPOESS changes. NOAA's strategic plan for GPM should include contingency plans to address the possibility of NPOESS and other microwave imager-sounder launch delays and/or sensor configuration changes.**

> ***Finding:*** **Many near-real-time applications of data from the MADRAS microwave sensor on board the French-Indian Megha-Tropique mission may be prevented because only three downloads per day to a single receiving station are planned. A minor investment and/or collaborative efforts with the MADRAS and other foreign satellite teams, such as FY-3, could greatly aid in maintaining the global precipitation constellation and could significantly enhance the GPM efforts on multiple fronts.**

> ***Recommendation 3.4:*** **NOAA should use its influence to facilitate free and swift access to all microwave imager digital data sets, whether they be U.S. missions or foreign satellites. NOAA should use its international influence to encourage foreign collaborators in order to create a robust microwave satellite constellation.**

CHALLENGES AND OPPORTUNITIES FOR FUTURE SPACE-BASED PRECIPITATION MISSIONS

In light of the GPM core satellite design and the status of the constellation satellites, the committee has identified five challenges for the GPM observational system that will pose opportunities for improving the next generation of space-based precipitation missions after the GPM era. The following five challenges are discussed throughout the report in the context of GPM planning: (1) measuring light precipitation in mid- and high latitudes, (2) measuring solid precipitation, (3) measuring precipitation over land, (4) spatial resolution, and (5) understanding precipitation processes. These challenges are also discussed in Chapter 5 in the context of planning for post-GPM precipitation measuring missions.

APPLICATION OF SPACE-BASED PRECIPITATION DATA

There are two major routes for routine integration of global satellite precipitation information in support of operations and associated mission-oriented research: (1) to construct near-real-time global and regional precipitation analyses on a regular time-space grid from satellite-inferred precipitation, and (2) to initialize the operational analysis-forecast cycle of atmospheric and land-surface components of NWP models through direct assimilation of satellite precipitation information such as precipitation estimates or radiances. An additional, specific route of application mentioned in this section is monitoring of tropical cyclone position and intensity. Global satellite precipitation information is integrated both inside and outside of government labs, including the development of research partnerships and agency support of universities to fully exploit the developing ability to infer precipitation and associated physical and dynamical processes from space-based observations.

Precipitation Analyses

Precipitation rates are inferred from microwave radiances, brightness temperatures (for infrared sensors), or reflectivity (for radar) (Box 3.2). This section presents background on precipitation analyses and suggestions for NOAA's contribution to improving the global precipitation products in preparation for the GPM era.

BOX 3.2
Precipitation Estimates from Spaceborne Sensors

Precipitation estimates from spaceborne sensors are derived from retrieval algorithms that convert the raw data into precipitation rates. These retrieval algorithms are based on empirical or statistical approaches (e.g., Arkin and Meisner, 1987; Wilheit et al., 1991; Ba and Gruber, 2001) as well as physically based techniques that use a radiative transfer model and a range of assumptions such as an assumed vertical distribution of precipitation and its particle size distribution (e.g., Spencer, 1986; Petty, 1994; Kummerow et al., 2001; Wilheit et al., 2003). A few satellite retrieval techniques use observed radiances and/or radar data for estimating precipitation (e.g., Haddad et al., 1997; Kuo et al., 2004; Chandrasekar et al., 2003b). Precipitation algorithms for GOES-R, for example, will rely on the use of microwave data to help calibrate them—an advancement in algorithm development, which has traditionally been strictly infrared based (R. Ferraro, NOAA, personal communication, 2006). There are also many approaches based on merged information from infrared and passive microwave sensors (e.g., Miller et al., 2001; Huffman et al., 2001; Todd et al., 2001; Joyce et al., 2004; Hong et al., 2005; Huffman, 2005).

Infrared Estimates of Precipitation

The strong correlation between infrared measurements and rain rates for warm-season convective systems that frequent the eastern and midwestern United States helps in monitoring flash flood events in concert with rain gauges and radar measurements. In other situations, however, the correlation declines, as does the value of this approach to inferring rain rate.

NOAA's Hydro-estimator (Hydro-E) method uses infrared satellite sources to estimate rain rate and, despite the drawbacks mentioned above, is popular in the operational setting because (1) it is simple to code and maintain the supporting software; (2) it works well in heavy summer rain, as noted above; and (3) results are quickly available since the technique does not wait for polar orbiter data (Vincente et al., 1998).

Passive Microwave Estimates of Precipitation

Polar-orbiting microwave sensors have been used in research and operational settings to create regional and global rain rate products for the last 20 years. Microwave imagers use external "hot" and "cold" load sources that provide vital calibration functions for inferring precipitation rates. These reference temperatures are critical to accurately quantify measured radiances. However, multiple problems exist with each microwave imager's calibration sources such as its stability within a given orbit or with seasons, sun contamination and/or reflectances off the spacecraft or sensors, and differences between a reference body and what the sensor actually views. These problems are eventually mitigated by painstaking multiyear studies (Wentz and Hilburn, 2006). The calibration effort could be greatly enhanced by planning in advance and incorporating internal calibration techniques that are now coming to fruition (Wentz and Hilburn, 2006).

> ***Finding:*** **Satellite microwave imagers have been calibrated using external sources that cause multiple problems not only for the given sensor, but also in cross-calibration of the microwave constellation. Internal calibration techniques are maturing and offer many advantages over external calibrations, and they will greatly enhance future precipitation-measuring missions and especially their contributions to GEOSS. Significant resources are wasted when it becomes necessary to going back after the fact to rectify poor data sets.**

> ***Recommendation 3.5:*** **NOAA should lead the international satellite community by proposing specific actions for the accurate calibration of all microwave imagers and sounders through cross-calibration and standard reference data sets and by implementing *internal* calibrations on all future microwave sensors.**

Physically based precipitation estimates from microwave sensors (using frequencies that are sensitive to hydrometeors) are more accurate than infrared-based approaches (Barrett and Beaumont, 1994). However, these microwave-based techniques suffer from the logistics of polar-orbiting platforms (e.g., poor data refresh rates) and modest spatial resolution. Plans for microwave imagers on the geostationary GOES-R platform would greatly aid temporal sampling, but resolution would still be limited. Although the higher frequencies are needed to improve spatial resolution, these frequencies have their own difficulties with regard to precipitation fidelity. More immediately, however, the temporal sampling has been markedly improved by the de facto microwave imager constellation that already exists (Figure 1.2, and earlier discussion in this chapter) and is a precursor to the GPM constellation. Despite these demonstrated improvements and the expected improvements from GPM, low spatial resolution remains a challenge for any space-based precipitation-measuring mission.

The ease of access to digital global research data in near real time from the present microwave constellation bodes well for efficient production of high-quality global precipitation estimates in the GPM era. Complicated multisatellite rain rate techniques have already been developed and are undergoing real-time calibration and validation. Significant advances are likely prior to the GPM core satellite launch because TRMM's precipitation radar data are being used to test these new methodologies.

Merged Precipitation Estimates

One promising approach to estimating global precipitation is to merge the best attributes of the infrared- and microwave-based estimation methodologies into one module. These positive attributes are the frequent temporal updates of infrared geostationary data and the more accurate, physically based microwave retrieval algorithms. Merged rain algorithms are being pursued by NOAA, NASA, DOD, academia, and foreign organizations, as fostered by the International Precipitation Working Group (IPWG) (Turk and Bauer, 2005a,b).

IPWG's goal is to provide "a forum for operational and research users of satellite precipitation measurements to exchange information on methods for measuring precipitation and the impact of space borne precipitation measurements in numerical weather and hydrometeorological prediction and climate studies."[4] This forum includes easy access to multiple, digital, near-real-time precipitation data sets and ongoing verification using set procedures applied routinely to each technique. Systematic biases can then be identified and methods developed to mitigate error sources as feasible. One example is available at *http://www.bom.gov.au/bmrc/SatRainVal/dailyval.html*.

Several "merged" precipitation techniques either are operational at NOAA or are under consideration in joint validation-comparison efforts (Table 3.2) and available in near real time. Each method incorporates both infrared and microwave data, but they differ in the exact microwave sensor suite and/or methodology that "blends" the two different data sets. Only when the large swath and high temporal infrared on geostationary satellites is included can we begin to address several very fundamental precipitation applications. For example, CMORPH uses frequent infrared-derived cloud motions to advect the microwave-based rain rates over time (Joyce et al., 2004), Multisatellite Precipitation Analysis builds up infrared-microwave rain relationships and then applies them to real-time data (Huffman et al., 2003), and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) uses geostationary and TRMM Microwave Imager data and incorporates a neural network approach (Sorooshian et al., 2000). The Naval Research Laboratory method uses all microwave imagers-sounders listed in Table 3.2. In addition, it incorporates TRMM precipitation radar data[5] and dynamically updates the infrared cloud-top temperature and rain rate tables around the globe (Turk and Miller, 2005).

GPM's 65-degree inclination will greatly increase the sampling of light rain and snow, and efforts will be needed to accurately validate retrievals under high-latitude environmental conditions from both the precipitation radar and the mi-

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[4] *http://www.isac.cnr.it/~ipwg/IPWG.html*

[5] Precipitation radar data are the most accurate space- or ground-based rain measurements. Although the TRMM Precipitation Radar's 200 km swath is small, this is offset by TRMM's low inclination and resultant many crossings with the higher-inclination microwave imagers.

crowave imager. New biases are likely to develop that must be addressed. In addition, infrared-microwave merged algorithms will face renewed tests due not only to the microwave weakness of these precipitation types, but to the poor geostationary look angle, spatial resolution, and in some cases, parallax.

Achieving optimal information integration from the suite of operational and research satellites is a challenging task. Appropriate sensor characterization and intercalibration (Box 3.3), fusion of the heterogeneous types of information, and skillful time-space interpolation are required. The novel ways of combining geostationary infrared and passive microwave observations each have their own inherent strengths and point the way forward to significant improvements in the GPM era. However, the error characteristics of the high-resolution products have yet to be adequately described, and opportunities for improvement by combining the various methodologies are only in the initial stages of development. Nonetheless, considerable progress has been made due to ready access to near-real-time digital data, modest computer processing requirements, and open exchange of ideas among members of the global precipitation community, including NOAA (e.g., through IPWG).[6] However, NOAA's participation in IPWG is on an ad hoc basis rather than in an official capacity. This poses limitations relating to (1) manpower restrictions at critical times while key personnel are committed to other projects, (2) computer processing infrastructure, and (3) travel funding.

> ***Finding:*** **NOAA has made excellent operational use of a robust merged rain rate algorithm (CMORPH) through its interactions with NASA and other groups in the United States and internationally. Such merged algorithms will be at the forefront of GPM applications since they take advantage of GPM-like sensors. Access to research sensors in near real time, the ability to process multiple data sets, and continued global cooperation will create mature modules before GPM becomes operational. IPWG is doing important work that will be invaluable to the GPM transition to operations, and NOAA scientists have been active and valued participants in IPWG. However, NOAA participation is on an ad hoc basis that limits NOAA's contribution and ability to lead IPWG efforts.**

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[6]The considerable global efforts to create real-time satellite-based rain estimates are covered in an extensive collection of material available on the IPWG web site (*http://www.isac.cnr.it/~ipwg/meetings/monterey/monterey2004.html*) and in associated meeting summaries (e.g., Turk and Bauer, 2005a). The web site includes the most complete inventory of existing operational algorithms (*http://www.isac.cnr.it/~ipwg/algorithms/algorithms-invent.html*) and summarizes the details of each method.

TABLE 3.2 Suite of Satellite-based Rain Rate Techniques Produced by NOAA or Available in Near Real Time for Comparisons, Validation, and/or Technical Idea Exchange[a]

	Hydro-E	CMORPH	PERSIANN	Naval Research Laboratory	Multisatellite Precipitation Analysis	Self-calibrating Multivariate Precipitation Retrieval (SCaMPR)
Spatial resolution	4-5 km	8 km	25 km 5 km soon	0.10 degree	0.25 by 0.25 degrees	4 km
Temporal resolution	15 minutes, uses ETA RH/TPW fields to adjust infrared rain	30 minutes, but finest time scale output is 3 hours	30 minutes	Instantaneous, but finest time scale output is 3 hours	3 hours	15 minutes
Data latency[b]	15 minutes	15 hours	1-4 hours soon	1-4 hours (low-Earth orbit)	10 hours	1-4 hours (low-Earth orbit)
Coverage	60 degrees North-South	60 degrees North-South	60 degrees North-South	60 degrees North-South	50 degrees North-South	20-60 North 130-60 West
Since (date)	2002	12/2002	03/2000	2002 (3-hour products archived since 2004)	01/1998	11/2004

Sensors Used						
Geostationary infrared	Yes	Yes	Yes	Yes	Yes	Yes
Passive microwave	No	Yes	Yes	Yes	Yes	Yes
TRMM Precipitation Radar	No	No	No	Yes	No	No
SSMI	No	Yes	Yes	Yes	Yes	Yes
AMSU	No	Yes	Yes	Yes	Yes	Yes
AMSR-E	No	Yes	Yes	Yes	Yes	No
SSMIS	No	Soon	No	Yes	No	No

[a]All algorithms are routinely run and digitally accessed through automated routines at NOAA, NASA, DOD, and other institutions.
[b]Delay in availability of product.
SOURCE: IPWG, 2006.

BOX 3.3
The Benefits and Challenges of Intercalibration

To integrate the observations and data products from different satellite systems, the measurements must be intercalibrated. Satellite instrument calibration activities take place throughout the lifetime of the instrument and beyond (through retrospective calibration) (WMO, 2006). Without intercalibration to remove biases, and without an understanding and quantification of the observation error characteristics, satellite radiances become far less useful for assimilation in NWP models. Without intercalibration, the observations are also of marginal value for climate applications, since drifts in satellite sensors can produce spurious trends in the time series, and jumps can occur in a time series constructed from different sensor observations.

Intercalibration of a heterogeneous set of sensors is a complex process. The removal of biases and identification of slow trends can require a substantial period of overlap (Wentz and Hilburn, 2006). Such overlap is particularly important when the constellation consists of observations from sensors with slightly different frequencies, scanning patterns, and orbital parameters that originate in several different nations. Various NWP organizations run reanalysis projects with the main objective to provide unbiased estimates of the atmospheric state based on an analysis system and data of very inhomogeneous quality and spatial and temporal distribution. The potential value of reanalysis products for intercalibration and bias removal has yet to be determined.

A global, space-based, intercalibration system would be part of an end-to-end capability consisting of onboard calibration devices (e.g., black bodies, solar diffusers); in situ measurements of the state of the surface and atmosphere (e.g., the Cloud and Radiation Testbed site, aircraft instruments with National Institute of Standards and Technology calibrations); radiative transfer models that enable comparison of calculated and observed radiances; and assimilation systems that merge all measurements into a cohesive consistent depiction of the Earth-atmosphere system (Goldberg, 2005).

The international operational satellite community has been moving rapidly toward the development and implementation of a comprehensive Global Spaced-Based Inter-Calibration System (GSICS) for GEOSS. The concept and strategy for this system were submitted by WMO and endorsed by the Coordination Group of Meteorological Satellites in 2005. The overarching goal of the system is to achieve operational intercalibration of the space component of the World Weather Watch Global Observing System that addresses the climate, weather forecasting, and other environmental needs of WMO members.

An implementation plan (WMO, 2006) describing the components of GSICS, the roles of participating agencies, a timetable for implementing the program, and coordination with other international programs was under review by the Coordination Group of Meteorological Satellites. GSICS will be implemented beginning in 2007, long before launch of the GPM core satellite. Consequently, it seems likely that links will develop between the GSICS operational system and the GPM research intercalibration program that includes operational satellites.

NOAA is a leading proponent of GEOSS activities. Therefore, it also seems likely that linkages will develop between NOAA GSICS activities and the GPM intercalibration program during the pre-launch and post-launch phases of GPM.

> ***Recommendation 3.6:*** **NOAA should formally support contributions of its scientists to IPWG so that NOAA's GPM program will help lead IPWG to the next generation. NOAA should fully fund its IPWG collaborations and ensure that its multisensor precipitation techniques result in state-of-the-art operational rain rate algorithms.**

Rainfall Distributions in Tropical Cyclones and Severe Storms

Knowledge of tropical cyclone rainfall distributions is inadequate from both the nowcast and the forecast perspective. Tropical cyclones cover a large domain, forming and growing over ocean regions void of land-based radars, and thus are prime candidates for satellite reconnaissance. Because both infrared- and microwave-based rain retrievals have limitations (as previously discussed), merged precipitation algorithms show potential for many monitoring tasks such as tropical cyclones.

To address a portion of the monitoring challenge, a product known as "R-CLIPER" (rainfall climatology and persistence) was devised to provide a first-order, real-time tropical cyclone rain estimate using high-resolution TRMM Microwave Imager data (Lonfat et al., 2004) (see Box 3.4). TRMM Microwave Imager data capture the rainfall gradients in tropical convective cells much better than coarser-resolution microwave imagers on the SSMI and SSMIS. The climatological rainfall values from R-CLIPER can be adjusted to storm characteristics such as size and speed. R-CLIPER rain rates are then combined with the official National Hurricane Center forecast track to provide near-real-time estimates of multiday rain accumulation forecast. This product is now used operationally at the National Hurricane Center.

NOAA's Tropical Rainfall Potential product provides forecasters with another estimate of landfalling tropical cyclone rain by advecting a static microwave-derived rain rate snapshot using the official forecast track and speed (Ferraro et al., 2005; Kidder et al., 2005). Although the Tropical Rainfall Potential product does not take into account any temporal rainband or eyewall precipitation fluctuations, it provides users with a rain estimate that can assist in warnings and emergency management actions.

At NASA's Goddard Space Flight Center, an inversion-based retrieval algorithm has been developed to estimate vertical profiles of precipitation ice water content and liquid water content in tropical cyclones from combined TRMM Precipitation Radar and Microwave Imager data (Jiang and Zipser, 2006). The proportion of liquid to ice content is important because it can have implications for tropical cyclone intensity. The algorithm was validated against aircraft-based measurements that demonstrated its strengths, particularly its accuracy with stratiform clouds. The validation process also demonstrated potential biases aris-

BOX 3.4
Tropical Cyclone Rainfall Estimates from TRMM Microwave Imager Data

Lonfat et al. (2004) have developed a tropical cyclone rainfall climatology product called R-CLIPER from TRMM Microwave Imager data. They processed TRMM Microwave Imager data for multiple years covering six ocean basins (Atlantic, East and West Pacific, North and South Indian Ocean, and South Pacific) and included all tropical cyclones of tropical storm strength or greater. The storms were then divided by intensity (tropical storms <33 ms^{-1}, CAT12 34-48 ms^{-1}, and CAT345 >49 ms^{-1}). The axisymmetric component of the tropical cyclone rainfall is represented by the radial distribution of the azimuthal mean rainfall rates, and the mean rainfall distribution is computed using 10 km annuli from the storm center to a 500 km radius. The composite rain rates vary by storm intensity and basin and provide forecasters with a baseline estimate for near-real-time applications.

ing from using only one type of data (e.g., microwave). Such biases are useful to know about in situations where only a single source is available. This algorithm is currently experimental and used only in a research mode.

Precipitation Climatology from Satellite Observations

The initial success of indirect estimation techniques based on infrared data and the prospects of continuing direct estimates of precipitation from operational microwave radiometers led the World Climate Research Programme to initiate the Global Precipitation Climatology Project (GPCP) in 1985 to provide global precipitation analyses for climate research (WCRP, 1986). The Global Precipitation Climatology Center in Germany (an element of the Global Energy and Water Cycle Experiment [GEWEX] and the World Climate Research Programme, and part of the WMO) is responsible for long-term archiving of global gauge precipitation. NOAA represents the United States in the WMO, and its international duty to precipitation programs at the Global Precipitation Climatology Center provides an opportunity to partner with other agencies such as NASA.

The GPCP initially focused on describing precipitation over the tropics and subtropics, and in 1986 it began producing preliminary 5-day precipitation estimates on a 2.5- by 2.5-degree grid. These estimates, derived from geostationary infrared imagery, were quantitatively useful for monthly totals as well as qualitatively useful for shorter time periods. Subsequently, geosynchronous infrared imagery was supplemented with low-orbit passive microwave data (Adler et al., 1992). The passive microwave estimates added to the accuracy of instantaneous rainfall amounts, but the sampling was sparser than from the infrared data. In addition, although both the infrared and the passive microwave estimates provide useful depictions of precipitation in many regions, both exhibit errors. Nonetheless, comparisons between infrared and passive microwave rainfall observations showed that combinations of different estimates improved rainfall analyses.

Two groups, at NASA and NOAA, proceeded to develop and implement global precipitation analyses for climate research. The NASA GPCP precipitation analyses combined infrared and passive microwave where both were available and otherwise used only passive microwave data, adjusted by gauge observations over land. To ensure complete geographic coverage, polar-orbiting infrared observations were later included for high latitudes. The NCEP Climate Prediction Center Merged Analysis of Precipitation product (Xie and Arkin, 1996) is based on a weighted average of available estimates, with weights determined by errors, combined over land with a gauge-based analysis. One version, based only on satellite-derived estimates and gauge observations, was spatially incomplete; another used model-based precipitation forecasts as an additional input and thus provided complete analyses. Products are now routinely produced from the NASA GPCP and the NCEP Climate Prediction Center Merged Analysis of Precipitation.

In a focused application of TRMM data to tropical cyclone rain rates, NASA used Multisatellite Precipitation Analysis to quantify the climatology of rainfall distribution in tropical cyclones that made landfall on the Gulf Coast during 1998-2004 (Jiang et al., 2006, and two unpublished papers[7]). Rainfall potential is defined by using the satellite-derived rain rate, satellite-derived storm size, and storm speed. This then feeds a landfall rain index, which can be used as a short-term rainfall prediction aid for landfalling tropical cyclones. Using the six landfalling tropical cyclones in the Gulf Coast in 2005 as test cases of this index approach, the average landfall rain forecast error was 10 percent (defined as predicted versus observed maximum storm total rainfall).

Data Assimilation

In 2005, an international workshop was held to examine the assimilation of satellite-observed cloud and precipitation observations.[8] This workshop is an example of an activity for identifying the best uses of precipitation data for a specific application such as data assimilation. Data assimilation is a statistical

[7]Jiang, H., J.B. Halverson, and J. Simpson, 2005, unpublished paper, "On the difference of storm rainfall of hurricanes Isidore and Lili, Part I: Satellite observatios and rain potential"; Jiang, H., J.B. Halverson, J. Simpson, and E. Zipser, 2005, unpublished paper, " On the difference of storm rainfall of hurricanes Isidore and Lili, Part II: water budget."

[8]Information about the 2005 workshop can be found online at *http://www.jcsda.noaa.gov/CloudPrecipWkShop*.

procedure that uses observations, a short-term forecast from a numerical model (the "background"), a forecast model (for 4D-VAR), and statistical assumptions about the error characteristics of the observations and model background to determine the best estimate (the "analysis") of the current state of the system. Precipitation information from the GPM mission may be used indirectly for assimilation into NWP, streamflow, and ocean salinity assessment models. (For specific examples of these uses, see: Reichle et al., 2001; Walker et al., 2003; Reichle and Koster, 2005; Crow et al., 2005.) Assimilation of precipitation data can be understood in two contexts: atmosphere and land surface. Assimilation techniques are described in this section, and the assimilation of GPM data is discussed later in this chapter.

Atmosphere

Satellites do not directly measure precipitation rate, but measure either outgoing radiation at the top of the atmosphere that may include an emission or a scattering signal from precipitation (e.g., radiances) or radar reflectivity. The rainfall retrieval inversion problem is seriously unconstrained and requires a substantial amount of a priori information and numerous assumptions. Moreover, NWP models produce precipitation forecasts that are in many areas and seasons better than satellite retrievals over land. In most cases, these forecasts are produced without any cloud- or rain-affected observations, implying that if moisture and dynamics are well described, the model physics can compensate for the lack of direct precipitation observations. Thus, data assimilation for better model initialization will benefit most from observations that cover the entire cloud-precipitation formation process and involve temperature, moisture, and potentially, dynamics, rather than only rainfall intensity estimates.

Multiple operational NWP centers, including NCEP, have demonstrated significant increases in their forecast skill by assimilating clear-sky (non-precipitation-affected) satellite radiances—particularly from passive microwave atmospheric temperature sounders (e.g., AMSU-A)—rather than inaccurate and coarsely sampled temperature and moisture profiles. Indeed, direct radiance assimilation represents the greatest advance in the global NWP community in the last decade. In addition, forecast performance in the Southern Hemisphere is now comparable to that in the Northern Hemisphere, despite the grossly unequal distribution of high-quality radiosonde data, largely due to the availability of global satellite sounder radiances.

Assimilation of satellite precipitation information (i.e., precipitation estimates or radiances) into NWP models has also been developing rapidly during the last decade, from the initial empirical approaches (e.g., Lord, 2004), to the variational assimilation of rain rates (Marecal and Mahfouf, 2000, 2002; Lord, 2004), and to the variational assimilation of precipitation-affected radiances (Moreau et al., 2004; Bauer, 2006a,b). Both empirical and variational techniques are being used in current operational or pre-operational NWP models. The empirical techniques adopt several assumptions about two-dimensional rain rate fields and then adjust the humidity or condensed water profiles based on cloud analyses and latent heat profiles from surface precipitation rates. Variational techniques use observation operators and their adjoints[9] to project information from space of the analyzed variables (e.g., temperature, moisture, wind) into that of the observations (e.g., precipitation rate, radiance) and back again in a consistent manner. For precipitation assimilation, the observation operator could be a simplified and (regularized) version of the moist physical parameterizations (and a radiative transfer model in case of radiance assimilation) that relates model state variables to the observations. Thus, a major advantage of variational techniques is (1) that they have the ability to assimilate observations that are not the same as the model variables, (2) that the assimilation is consistent with the model physics, and (3) that spatially and temporally heterogeneously distributed observations are optimally treated.

The assimilation of precipitation (and cloud) information is fundamentally more difficult than assimilating temperature, humidity, or wind information. Precipitation is a complex meteorological variable that routinely undergoes dramatic spatial and temporal fluctuations that are not fully understood, much less modeled in near real time. This is particularly problematic for sub-grid-scale processes such as convection. Consequently, satellite-derived precipitation measurements are not yet assimilated into NWP forecast models at many forecast centers. The specific difficulties include (1) limited NWP model ability to accurately forecast quantitative precipitations; (2) inadequate moist physics for clouds, convection, and sub-grid-scale precipitation (retrievals and radiance assimilation are constrained by model microphysics) that includes difficulties relating observed variables to the model variables linked to precipitation; (3) nonnormal observation and background error distributions; (4) non-instantaneous sampling of rapidly evolving rain fields that introduces temporal errors in the data sets; (5) poor knowledge of the statistical properties of clouds; (6) difficulty validating satellite precipitation retrievals; (7) inability to accurately map three-dimensional rain rate structure and fully understand resultant latent heating profiles; and (8) lack of sensitivity of the measurements to drizzle and snowfall. Although the list of hurdles is daunting, progress is feasible through a well-supported, coordinated, multiyear approach spanning several disciplines.

[9]For this example, the adjoint is the matrix transpose of the observation operator (tangent linear version of the moist physical parameterization model).

Land Surface

Land Data Assimilation Systems (LDAS), which use available observations to modify model background fields, can provide a more accurate and unbiased evaluation of initial land-surface states by reducing the accumulating biases in coupled system forecasts of moisture and energy reservoirs.[10] Thus, LDAS is similar to atmosphere data assimilation in that it uses available observations to modify a short-range model forecast to provide initialization for a forecast run. Remotely sensed precipitation and soil moisture information is used increasingly in LDAS that may be coupled with atmospheric NWP models (e.g., Rizvi et al., 2002; Drusch et al., 2005).

Small-scale spatial and temporal variations in precipitation and available energy, combined with land-surface heterogeneity, cause complex variations in processes related to land-surface hydrology. Characterization of the spatial and temporal variability of the terrestrial water and energy cycles is critical for an improved understanding and modeling of land-atmosphere interaction and the impact of land-surface processes on climate variability.

The reservoir and profile of soil moisture and the surface heat balance are the crucial controlling elements for land-surface hydrological processes. Although land-surface layer "wetness" can be inferred from space-based measurements, the total reservoir and profile of soil moisture cannot be directly determined from existing space-based observations. Except for a few specialized local networks, whose soil moisture observations are primarily of value for localized monitoring and development of land-surface models, the total reservoir and profile of soil moisture cannot be determined directly from surface observations either.

It is essential to address the observational deficiency of total reservoir and profile of soil moisture to provide information needed for applications such as river stage forecasts, drought monitoring, and crop yield outlooks. Semiempirical land-surface models have been developed to quantify and monitor surface hydrological conditions. These models provide indirect estimates of soil moisture by partitioning precipitation input between surface storage (snow water content), soil moisture recharge, evapotranspiration, and surface and subsurface runoff.

Land-atmosphere interactions influence weather and climate variability on a variety of spatial and temporal scales. Because an accurate knowledge of these processes and their variability is important for weather and climate predictions, most forecast centers have incorporated land-surface schemes in their NWP models. Unfortunately, biases develop in model-generated water and energy storage that can continue to grow in the closed, internally cycled, coupled model forecast system. Because these biases can negatively affect forecast accuracy, the NWP

[10] See *http://ldas.gsfc.nasa.gov*.

community has been motivated to impose ad hoc corrections to the land-surface states to limit this drift.

The U.S. program for the development, application, and improvement of LDAS components is being led by scientists at NASA's Goddard Space Flight Center and NOAA's NCEP, in collaboration with researchers at Princeton, the University of Washington, and the NWS Office of Hydrologic Development. This program is focused on the development and application of an LDAS for North America (Mitchell, 2004) and an LDAS for global applications (Rodell et al., 2004).

A blended precipitation product is used for the North America LDAS. For the United States, this product is derived by combining 3-hourly precipitation from the NCEP regional model with hourly Doppler radar precipitation and daily rain gauge precipitation. For Canada and Mexico, only the regional model output is used. Several of the current high-resolution satellite-based global precipitation analyses (e.g., high-resolution precipitation products) are being used to force the global LDAS and validate precipitation. NCEP's Environmental Modeling Center runs the LDAS uncoupled to any atmospheric model and participates in a collaboration on the global LDAS with other agencies.

Operational Application of Precipitation Assimilation Techniques

Despite the difficulties of assimilating precipitation, a few centers, such as NCEP, Japan Meteorological Agency (JMA), and the European Centre for Medium-range Weather Forecasts (ECMWF) are assimilating precipitation information operationally. In the NCEP regional analysis (i.e., North American Model), precipitation estimates from SSMI, TRMM Microwave Imager, and rain gauges and ground-based radar (over the continental United States) are assimilated using a nudging technique. The analysis has a real-time data cutoff of 45 minutes after the analysis time (e.g., 45 minutes after each 6-hourly model run at 00:00, 06:00, 12:00, and 18:00 Coordinated Universal Time). All data to be assimilated must arrive prior to the data cutoff time. The model temperature, water vapor, and cloud liquid water profiles are adjusted over a 6- to 12-hour window so that the model recomputed rainfall matches the observed (Y. Lin, NOAA NCEP, personal communication, 2006).

The NCEP Global Forecast System has a real-time data cutoff time of 2 hours and 45 minutes. The TRMM Microwave Imager and SSMI rainfall estimates over land and ocean are averaged at a 1-degree resolution, and a transformed rain rate is then assimilated variationally, with an assigned observation error that differentiates between land and ocean. The assimilation process changes the temperature, moisture, cloud water mass, and horizontal wind fields.

In the Global Forecast System, precipitation assimilation primarily reduces excessive rain rates and, to a lesser extent, increases light rain rates (R. Treadon, NOAA, personal communication, 2006). The impact is greater over oceans than land. Overall, the forecast impact is difficult to quantify with several upgrades combined and tested at once in addition to precipitation, although some relative improvement is shown in the 0- to 24-hour predicted tropical rainfall, forecast wind fields, and tropical cyclone track prediction. NCEP has noted that clear-sky radiance assimilation has a greater impact on forecast precipitation than rain rate assimilation (R. Treadon, NOAA, personal communication, 2006). Given this, plus the ability of the new Joint Center for Satellite Data Assimilation Community Radiative Transfer Model to simulate radiances in cloudy and precipitating fields of view, NCEP plans to move to the direct assimilation of precipitation-affected radiances (R. Treadon, NOAA, personal communication, 2006). Other potential improvements may come through better characterization of the observation and background errors; implementing flow-dependent background error covariances; new analysis systems (GSI and eventually 4D-VAR), and improved model physics and convective scheme (used for assimilation) (Lord, 2004). Lord (2004) also addressed the importance of bias-correcting the observations so that they are consistent with the simplified convective scheme used for assimilation.

At ECMWF, precipitation-affected radiance assimilation was recently added to the operational forecast suite (Bauer, 2005). A one-dimensional variational (1D-VAR) retrieval is used to obtain temperature and moisture profiles from TRMM Microwave Imager and SSMI radiances in clouds and precipitation over oceans. From the 1D-VAR retrievals only moisture is subsequently assimilated as total column water vapor in their global, four-dimensional variational analysis (4D-VAR) system. ECMWF plans to move to direct assimilation of precipitation-affecting radiances in its 4D-VAR system in 2007 (Bauer et al., 2006a,b).

At JMA, the Radar-AMeDAS (dense network of surface observations including precipitation) composite precipitation data are used in the regional and mesoscale models (Kamiguchi et al., 2005; JMA, 2006). Doppler radar radial wind and precipitable water and rain rate derived from the microwave radiometer on SSMI, TRMM Microwave Imager, and Aqua AMSR-E are used in the mesoscale model. Precipitation information is assimilated using the adjoint of the moist physics that includes both large-scale condensation and convective adjustment (Sato et al., 2004).

Even though precipitation assimilation is now operational at several NWP centers, much basic research is still needed to fully exploit the observations. This is discussed in Chapter 4 in the context of NOAA preparations for exploiting GPM data.

Monitoring Location and Intensity of Tropical Cyclones and Severe Storms

Upper-level clouds commonly prevent satellite data analysts from accurately determining tropical cyclone location and intensity using visible-infrared imagery from geostationary and polar-orbiting sensors. Fortunately, some microwave frequencies respond sharply to the frozen hydrometeors and heavy rain characteristics of intense tropical cyclone convective rainbands and eyewall development. Large brightness temperature contrasts permit microwave imagers and sounders with 85-91 GHz channels (i.e., SSMI, SSMIS, TRMM Microwave Imager, AMSR-E, AMSU-B) to supply vital tropical cyclone information (Lee et al., 1999, 2002; Hawkins et al., 2001; Simpson, 2003).

Multiple U.S. centers use the passive microwave sensors operationally for tropical cyclone structural details. NOAA's Tropical Analysis and Forecasting Branch and Satellite Analysis Branch provide the National Hurricane Center with storm location and intensity values for all storms in the Atlantic and Eastern Pacific using microwave products created and distributed by the Naval Research Laboratory and the Fleet Numerical Meteorology and Oceanography Center. The storm-centered microwave products are updated within 1-3 hours of satellite data acquisition and are available worldwide.[11] DOD's Joint Typhoon Warning Center provides multiday forecasts for all storms in the Pacific Ocean, Indian Ocean, and Southern Hemisphere where approximately 80 systems per year typically occur. The Joint Typhoon Warning Center has dedicated satellite analysts who provide the typhoon duty officer with routine storm position and intensity estimates for all active systems. In addition, DOD's Air Force Weather Agency provides backup resources and creates storm fixes for both the Joint Typhoon Warning Center and the National Hurricane Center using these data sets. The ability to understand storm temporal structure changes via rainband and eyewall configuration trends is crucial to catching storms undergoing rapid intensification, concentric eyewall cycles, and shear and cannot be done with visible-infrared data alone.

NCEP plans to implement an extension of the Weather Research and Forecasting Model for hurricane track and intensity forecasting operationally in 2007. The Hurricane-WRF (HWRF) system couples a wave model, an ocean model, a land-surface model, and an atmosphere-ocean boundary-layer model.

One of the most significant modeling challenges to improving numerical forecasts of hurricane structure and intensity in high-resolution hurricane models is the initialization of the hurricane vortex. To advance this effort in HWRF, NOAA's Environmental Modeling Center is developing situation-dependent background error covariances that will be incorporated into a local data assimilation scheme. The immediate goals are to assimilate real-time Doppler radar data from reconnaissance aircraft and coastal WSR-88D radars near land. Future plans call for assimilation of radar reflectivity data and precipitation-affected radiances.

[11]Available at *http://www.nrlmry.navy.mil/tc_pages/tc_home.html* and *http://152.80.49.216/tc-bin/tc_home.cgi*.

POTENTIAL APPLICATIONS OF GPM DATA

The availability of GPM-like data from both the TRMM Precipitation Radar and the TRMM Microwave Imager and access to operational and research microwave sensors (SSMI, AMSR-E, WindSat, SSMIS, and AMSU-B) allow realistic predictions of GPM applications now. In addition, they allow testing and refining of methodologies in advance of GPM core satellite launch. Access to near-real-time digital data sets, computer processing power, and automated software has created a wealth of web-based products and databases that feed a diverse and growing user community. Precipitation information serves both near-real-time and non-real-time functions in NOAA operations. Near-real-time applications of satellite precipitation estimates include (1) data assimilation into global and regional models (e.g., hurricane forecasts), and (2) merged or blended global precipitation products (e.g., CMORPH). Non-real-time applications include (1) cross-calibration of GPM's precipitation radar with other satellite passive microwave precipitation estimates, (2) seasonal models for drought and hydrologic forecasting, and (3) climate modeling.

GPM data users are in three principal areas of application: weather prediction and monitoring, hydrology, and climate. This section describes potential applications of GPM data in an operational environment, focusing specifically on NOAA (the committee's second task).

Numerical Weather Prediction

Data Assimilation

The ultimate goal of NWP is to create useful and accurate forecasts, especially for inclement weather. Areas with clouds and precipitation are often dynamically active, and subsequent NWP forecasts are often sensitive to initial conditions in these areas. Thus, improving their initial conditions should improve the downstream forecasts. Improvement in the initial conditions of the models will result from improved precipitation estimates from GPM and other sensors calibrated by GPM. Moreover, few conventional observations are available for these areas, and satellite data assimilation is essential. Microwave imagers and sounders have improved the ability to monitor near-real-time clouds and rain regionally and globally, but parallel efforts to incorporate these data sets within NWP models have not kept pace because of the complex nature of precipitation variation. Availability of GPM data will help in this regard. The GPM mission has advantages over the TRMM mission for data assimilation and NWP: the improved precipitation rate estimates of the dual-frequency precipitation radar on the GPM core satellite (particularly for light rain) (see Chapter 2) and the increased sampling capacity of the 65-degree inclined orbit of the GPM core satellite.[12] Although the swath width of the GPM precipitation radar may limit its utility for assimilation, the relative accuracy of the precipitation radar makes it valuable for validation and calibration of rain rate algorithms for microwave imagers.

Even though operational NWP models do well predicting the clouds associated with large-scale organized systems, quantitative precipitation forecasts generally have limited utility beyond 2-3 days. Two contributing factors are that the NWP models more accurately reproduce large-scale motions than cloud microphysics, and the subsequent precipitation forecasts are sensitive to less accurately analyzed or forecast fields, such as vertical motion. The high-precision precipitation radar measurements of horizontal and vertical cloud structure and microphysical elements will provide useful validation data for the development of improved model physical parameterization schemes. Assimilation of the microwave imager precipitation information may help improve the initial conditions required for accurate short-range forecasts of precipitation.

High-quality precipitation data are also required for validation of precipitation forecasts. The precipitation radar on GPM will be valuable for this purpose because it provides one of the few sources of precipitation validation data over oceans. The extensive, international ground validation data will also prove useful for validation of NWP precipitation forecasts.

To realistically specify real-time rain rates in NWP model analyses, definition of rain rate profiles is critical. Without this key three-dimensional information, precipitation data assimilation must rely on less effective methods. For example, although rain rates can be inferred from microwave imager and sounder data, only radar can actually retrieve vertical profiles. The TRMM precipitation radar is the first satellite sensor to demonstrate that rain rate profiles are feasible from satellite observations (Chapter 2), and the dual-frequency precipitation radar on the GPM core satellite will continue this unique data stream.

The radar swath widths of TRMM and the GPM core satellite do not provide the coverage required for nowcasting and/or NWP initialization efforts. Nonetheless, precipitation radar data have been useful for NWP model validation. For example, Benedetti et al. (2005) used precipitation radar data to validate the assimilation of TRMM Microwave Imager and SSMI precipitation-affected radiances into the ECMWF model. The GPM constellation not only has the potential to monitor near-real-time rain events, but with proper planning and support, the data can have an impact on NWP advancements.

[12]Compared to TRMM's orbit between 35 degrees latitude North and South. Details about the GPM precipitation radar frequencies and swath widths are presented in Chapter 1.

Monitoring Tropical Cyclones and Severe Storms

In conjunction with the sensors on the constellation spacecraft, the microwave imager on the GPM core satellite will have resolution similar to the TRMM Microwave Imager and superior to the SSMIS and microwave sensors flying on the DMSP and NPOESS operational satellites in the 2010-2015 time frame. Thus, the GPM Microwave Imager rainfall data will be crucial in mapping tropical cyclone rainfall, updating R-CLIPER values for future applications, and addressing the global need to monitor potential flooding disasters caused by landfalling tropical cyclones. Flood fatalities are especially likely in developing countries that have large coastal populations, low elevations, and little weather infrastructure to warn about impending heavy rains (Hossain and Katiyar, 2006). GPM near-real-time data sets could be key ingredients to life-and-death evacuation decisions.

In addition, GPM will have a direct and measurable positive impact in supporting NOAA's goal to protect life and property from tropical cyclone damage in the continental United States and countries that rely on U.S.-derived information by improved forecasts of landfall location and intensity. Microwave measurements from GPM's precipitation radar and microwave imager will give analysts cloud-free views of tropical cyclone structure. Near-real-time information on storm location and structure (highly correlated with intensity) from similar sensors on TRMM has proven operationally beneficial at the National Hurricane Center (NRC, 2004).

Hydrometeorological Applications

Data from the GPM core and constellation satellites will be valuable for a wide range of applications in hydrometeorology and oceanic meteorology.[13] These applications evolve primarily from spaceborne precipitation estimates as well as remotely-sensed soil-moisture and ocean-salinity information. Because of the broad geographic coverage of the GPM mission, GPM data will be particularly valuable in areas of poor ground-based rainfall data for inferring hydrological variability and improving multisensor quantitative precipitation estimates.

By underpinning high-quality, high-resolution precipitation products, GPM will support soil-moisture estimates that feed flood forecast models. Such models rely on precipitation estimates and surface radiative balance as the fundamental variables to calculate soil-moisture content in semiempirical land-surface

[13] *Hydrometeorology*, according to the American Meteorological Society *Glossary of Meteorology* (2nd edition, 2000), is the "study of the atmospheric and terrestrial phases of the hydrologic cycle with emphasis on the interrelationship between them," while *oceanic meteorology* relates to the "study of the interaction between the sea and the atmosphere."

model schemes (e.g., LDAS), where precipitation is partitioned between runoff and soil-moisture recharge. Such analyses are particularly valuable for land areas where ground-based precipitation observations are inadequate. Recent examples of successful application of satellite-based precipitation to hydrologic modeling for streamflow forecasting indicate opportunities for GPM applications (see Yilmaz et al., 2005; Moradkhani et al., 2006).

The typical spatial resolution of global, satellite-based, high-resolution precipitation product analyses is comparable to that of LDAS components (i.e., 10 to 20 km). The ability to use these products in an operational setting will depend on their availability in the time frame of forecast cycle operations. GPM precipitation data have the potential to contribute to both the further development and the operational application of regional and global LDAS components through improved input and validation of precipitation. GPM data will likely have the greatest impact on global LDAS by improving the quality of the high-resolution precipitation analysis products for the large land areas of the world where surface observations are sparse or not available in a timely manner.

Two satellite missions that will potentially overlap with GPM—GOES-R and Aquarius—could enhance the contribution of GPM data to a number of hydrometeorological applications. For example, GOES-R data will be available at 5-minute intervals. In combination with infrared-microwave precipitation estimates with radar-calibrated GPM constellation data, these data will benefit flash flood forecasting. Freshwater input to the ocean surface (by means of precipitation) and ocean salinity are two other potential applications in which GPM data will be useful. The Aquarius mission will measure sea-surface salinity and is a joint project between NASA and the Space Agency of Argentina (Comisión Nacional de Actividades Espaciales). Combining sea-surface salinity measurements[14] with inferred precipitation from GPM will be helpful in closing the marine hydrological budget. Furthermore, Aquarius could be a validation tool, albeit an indirect one, for NOAA's estimates of precipitation over the ocean.

While the satellite-based precipitation estimates may have achieved reasonable accuracy to be useful for many purposes, the soil moisture (or more appropriately labeled "surface wetness") and ocean salinity estimates from spaceborne platforms are still highly experimental at this point (and thus likely not as useful in a quantitative sense) and only available with limited coverage in space and time.

[14]The surface salinity depends on air-sea freshwater fluxes from precipitation and evaporation, as well as advection and mixing in the upper ocean.

Climate Applications

Precipitation Climatology

The primary requirements for satellite-related precipitation data for climate applications are high absolute accuracy and long, stable, and consistent time series. GPM would contribute to such applications by extending the time series that began with the launch of TRMM. The limitations of the precipitation climatology developed from TRMM data include (1) a short record (to date); (2) a coarse time-space sampling (i.e., the mission was designed to resolve five-by-five-degree monthly averages); and (3) geographical limitations (35 degrees latitude North and South). Nevertheless, because of the previous meager level of knowledge, TRMM Microwave Imager data have been extremely valuable for describing the large-scale features of the tropical and subtropical precipitation regimes, including individual realizations of the El Niño-Southern Oscillation cycle. In addition, TRMM precipitation radar data have revealed the synoptic climatological features of the precipitation patterns associated with the evolution of tropical cyclones. GPM offers the opportunity to significantly extend the length and geographic coverage of intercalibrated precipitation climatology.

Precipitation Analyses

GPCP precipitation analyses, along with a new generation of high-resolution precipitation products, exploit passive microwave data from the existing array of polar-orbiting satellites to extend the analysis domain into the high latitudes. As noted earlier, high-resolution precipitation product analyses are primarily used for monitoring and nowcasting weather and short-term climate variability. Some of these analysis schemes exploit TRMM data for intercalibration of passive microwave observations, but the lack of TRMM-type core satellite observations in higher latitudes limits intercalibration outside the tropics and subtropics. GPM will extend these limits from 35 degrees to 65 degrees latitude North and South (the midlatitudes).

Efforts are under way at the Climate Prediction Center to extend the short CMORPH time series, which began in December 2002, backward to include the entire period since 1998 when TRMM data became available. It is doubtful whether passive microwave sampling prior to that time is sufficient to generate reliable global precipitation analyses using the CMORPH method (J. Janowiak, NOAA, personal communication, 2006). Further backward extension of the time series would have to rely heavily on infrared-derived precipitation estimates and would almost certainly result in a discontinuity in the time series and poorer-quality analyses. Thus, the length of the high-resolution global time series derived from satellite passive microwave data is likely to be limited to the period since 1998 but would be greatly extended by GPM and, in particular, would be greatly helped in terms of intercalibration if TRMM and GPM overlap.

Global Precipitation Climate Data Records

The construction of continuing, stable, and accurate global precipitation analyses from observations from a continually changing international constellation of research and operational satellites is a fundamental but daunting challenge for the development of satellite-based global climate data records.[15] Fulfillment of this task depends on a number of factors, of which the following two are central:

1. Climate data records depend on the maintenance of an international constellation of satellites that provide the routine time-space sampling needed for high-quality global precipitation analyses. For example, the design sampling interval of the GPM constellation of passive microwave sensors is 3 hours. International coordination to improve the phasing of polar-orbiting satellites could be a factor for improving sampling.
2. Climate data records depend on an ongoing and extensive international program for intercalibration of satellite radiances. Without intercalibration to remove biases, and an understanding and quantification of the error characteristics of the observations, the measurements are of marginal value for climate applications, since drifts in satellite sensors can produce spurious trends in the time series, and jumps can occur in a time series due to systematic biases from different sensor observations.

The planned observational and calibration-validation programs of the GPM mission will address many of the current deficiencies that limit the development of satellite-based global precipitation climate data records.

SUMMARY

The best operational uses of GPM data at NOAA will be weather forecasting, hydrologic applications, climate applications, and global precipitation climate data records. Prior to the launch of the GPM core satellite, NOAA can initiate improvements in current sources of precipitation data and improvements in data products to enhance the operational benefits of the GPM mission. Chapter 4 outlines additional preparation activities at NOAA for optimal use of GPM data by the launch of the GPM core satellite.

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[15] A climate data record is a data set designed to serve as a climatological basis for diagnosing and studying year-to-year climate variations and decade-to-decade climate change (NRC, 2000). Intercalibration and data continuity are critical components of climate data records. In contrast to environmental data records, which are produced and generally used in real time, the strategy for the production of climate data records involves repeated retrospective reanalysis and refinement, usually based on additional data and information from multiple sources (e.g., improved algorithms).

4

NOAA Preparation for Early Exploitation of New Space-Based Precipitation Data

The National Oceanic and Atmospheric Administration (NOAA) can take steps to ensure that its operational forecast models, forecasters, and product users are ready for data from the Global Precipitation Measurement (GPM) mission by the launch of the GPM core satellite. This chapter is organized into two sections: the NOAA-NASA (National Aeronautics and Space Administration) partnership and NOAA preparation activities for GPM.

NOAA-NASA PARTNERSHIP

The context for a NOAA-NASA partnership on GPM is that GPM is a science mission that will provide data and research that NOAA will use to advance capabilities for numerical weather prediction (NWP) (Hou, 2005). NASA has stated that NOAA's operational needs cannot be a driver of requirements or costs of the mission and that each agency will fund its own participation in the program (Neeck, 2005). Since NASA is not an operational agency, there will not be a direct connection between NOAA's operational requirements and NASA mission requirements. Nonetheless, the NOAA-NASA partnership on GPM will be most effective and mutually beneficial if it is a two-way interaction involving NOAA contributions to the mission and mission contributions to NOAA operations. To ensure NOAA's readiness to exploit GPM data when they become routinely available, and considering the possibility of a "potential NOAA takeover phase" of GPM that would potentially begin 5 years after launch (Dittberner, 2006),[1] a coordinated effort by NOAA and NASA is needed for planning roles and responsibilities in all phases of the mission (Recommen-

[1]This is a concept at this point because NOAA is not budgeted to take over the NASA satellite during the GPM post-launch phase.

dation 2.1). This section summarizes a number of activities from which such a partnership can grow.

NOAA-NASA GPM Research and Operations Group

The need for a NOAA-NASA partnership on GPM was acknowledged in a 2002 NOAA workshop report (NOAA, 2002). Also in 2002, NOAA and NASA expressed a mutual desire to collaborate on GPM. This resulted in the formation of the NASA-NOAA GPM Ad Hoc Working Group. The group defined partnering opportunities between the two agencies in a white paper, "NOAA Cooperation with NASA on the Global Precipitation Mission" (see Appendix A). Through its involvement in this group, NOAA participated in GPM workshops and planning meetings, design reviews, and other events. In addition, NOAA contributed to a white paper that helped secure the inclusion of high-frequency channels on the GPM Microwave Imager. The ad hoc group is now known as the NOAA-NASA GPM Research and Operations Group and is developing a "capability implementation plan" for GPM based on NOAA requirements. This plan will define short-, mid-, and long-term goals for GPM from NASA and NOAA perspectives (Appendix B).

In parallel with this targeted GPM collaboration and in response to a recommendation from the National Research Council (NRC, 2003), NASA and NOAA established the Joint Working Group (JWG) on Research and Operations in 2004.[2] The JWG identified global precipitation as one of five initial capabilities for which to prepare a research-to-operations plan. The NOAA-NASA GPM Research and Operations Group functions as a subgroup of the JWG to help develop the research-to-operations plan.

NASA's Precipitation Measurement Missions Science Team

Over the past 3 years, NASA has selected NOAA scientists (four at present) to serve on the Precipitation Measurement Missions science team. Support for NOAA scientists on the science team is term-limited and up for a recompetition in fiscal year (FY) 2006 under NASA's formal process for Research Opportunities in Space and Earth Sciences. At the time of writing, NOAA does not directly fund its employees' participation on this science team (Ferraro, 2006). Consequently, NOAA's involvement in the science team is not guaranteed, especially since NASA's proposed FY 2007 budget has been cut.[3]

[2] The JWG is mandated in NASA's Reauthorization Bill (section 306) (see Appendix C).

[3] In an effort to formalize NOAA's contributions to GPM planning, NOAA personnel have participated in the last two exercises of the NOAA Planning, Programming, Budgeting, and Execution System. A GPM Program element has been established and possible funding vehicles (e.g., National Polar-orbiting Environmental Satellite System Data Exploitation) are being explored to help support this element.

Joint Center for Satellite Data Assimilation

The Joint Center for Satellite Data Assimilation (JCSDA) is an interagency group with the goal of accelerating the abilities of NOAA, NASA, and the Department of Defense (DOD) to ingest and effectively use observations from Earth-orbiting satellites (see JCSDA section below). Such uses include improving weather forecasts in operational NWP models, improving seasonal-to-interannual climate forecasts, and increasing the physical accuracy of climate data sets. Through these activities, JCSDA will strive to ensure that the United States realizes the maximum benefit of its investment in space as part of an advanced global observing system.

International Precipitation Working Group

The International Precipitation Working Group (IPWG) is discussed in Chapter 3 (see "Merged Precipitation Estimates"), with a corresponding finding and recommendation. Although IPWG provides an important opportunity for NOAA to partner with NASA on GPM, NOAA's active and valued participation in IPWG is on an ad hoc basis, limiting its contribution and ability to lead GPM efforts through IPWG.

> ***Finding:*** **The NASA-NOAA partnership for GPM consists of numerous joint planning activities. NOAA's overall participation in collaboration activities with NASA is ad hoc, lacking in formal funding, or outside of NOAA's control. These factors limit NOAA's ability to formally engage in GPM planning. The formal establishment and support of a NOAA steering group on space-based precipitation missions could serve as a focal point at NOAA to coordinate effective GPM partnership activities with NASA and thus expand the benefits to NOAA's applications. The NOAA steering group on space-based precipitation missions could also oversee the implementation of the GPM strategic plan recommended by this committee (Recommendation 2.1).**

> ***Recommendation 4.1:*** **NOAA should formally support the NOAA-NASA GPM Research and Operations Group, the NASA Precipitation Measurement Missions science team, JCSDA, and IPWG through the establishment of a NOAA steering group on space-based precipitation missions, through direct support of these partnership activities, and/or through support of individual NOAA scientists. The NOAA steering group on space-based precipitation missions should serve as a focal point at NOAA to coordinate GPM partnership activities with NASA and should oversee implementation of the GPM strategic plan recommended by this committee.**

NOAA PREPARATION FOR USE OF GPM DATA

NOAA preparations for use of GPM data fall into 11 categories:

1. NASA-NOAA Cooperative Research and Development Activities
2. Satellite Data Exchange
3. Intercalibration
4. Ground Validation Support
5. Data Products
6. Archiving and Distributing Precipitation Data
7. Infusion of New Technology
8. Data Assimilation
9. Model Physics Development
10. Data Impact Evaluation
11. User Education and Training

Each category is presented in the following sections with a detailed discussion of activities NOAA may consider.

1. NASA-NOAA Cooperative Research and Development Activities

NOAA is already participating in the planning process for precipitation missions (see previous section), and opportunities remain for enhanced involvement. The NOAA-NASA partnership will be especially important in algorithm prototyping (led by NASA) and transition to operations (led by NOAA). Activities at the National Centers for Environmental Prediction (NCEP) in collaboration with JCSDA (see the section on assimilation) are examples of an effective NOAA-NASA partnership; other partnership opportunities will arise in the GPM ground validation program (see later sections).

2. Satellite Data Exchange

NASA will need quick access to NOAA satellite data for calibration and validation of GPM data and for research. These data include visible-infrared and microwave measurements from NOAA-operated satellites or satellite data that NOAA anticipates receiving in near real time, through collaboration with DOD in some cases. The sources of such data include the Geostationary Operational Environmental Satellites (GOES), Polar-orbiting Operational Environmental Satellite (POES), National Polar-orbiting Operational Environmental Satellite System (NPOESS), NPOESS Preparatory Mission (NPP), and satellites in the Defense Meteorological Satellite Program (DMSP). In turn, NOAA scientists will need to access GPM data as quickly as possible following quality control by NASA. Such exchange will be smoothed if it falls under existing agreements.

3. Intercalibration

Intercalibration ensures consistency and stability of the precipitation time series; without intercalibration, the full benefit of the observations will not be realized. Accurate intercalibration of GPM constellation measurements is thus a key to the success of the GPM mission. By contributing to this effort, NOAA will be well positioned to use GPM data when they become available.

As NWP methods turn to assimilation of radiances rather than algorithm-dependent physical parameters, intercalibration of satellite radiances and standardized quality control become increasingly important for operations and applications. The GPM approach to intercalibration is to quantitatively relate the radiances from different sensors that view the same target to allow consistent and unbiased measurements over the globe (Flaming, 2004). The core satellite will provide information on regional and seasonal rainfall structures that will serve as an a priori database for simpler radiometers (Kummerow, 2006). Co-location of the dual-frequency precipitation radar and the GPM Microwave Imager provides the opportunity to calibrate radiometric measurements made by the GPM Microwave Imager using the high-precision measurements of clouds, cloud structure, and rainfall processes by the precipitation radar. This can then be extended to intercalibration of the members of the GPM constellation as orbital overpasses occur (Flaming, 2004). A substantial effort has to be made for improving combined passive-active precipitation retrieval algorithms to fully exploit the strengths of individual sensors.

Since GPM is designed as a prototype mission for the Global Earth Observation System of Systems (GEOSS) (Hou, 2005), it provides an opportunity to prepare for transition of the GPM research intercalibration program to an operational GEOSS intercalibration activity (Chapter 1). The international operational satellite community has been moving rapidly toward implementing a comprehensive Global Space-Based Inter-Calibration System (GSICS) for GEOSS. As noted in Chapter 3, it now seems likely that GSICS will be implemented long before launch of the GPM core satellite. Since NOAA is a leading proponent of GEOSS activities, linkages will likely develop between NOAA GSICS activities and the GPM intercalibration program during the pre-launch and post-launch phases of GPM.

4. Ground Validation Support

The ground validation program of GPM (Chapter 1) is a crucial element that will help characterize errors, quantify measurement uncertainty, provide a measurement standard against which to assess performance, and help improve the retrieval algorithms. The goal of this program is to provide ground observations for direct satellite product assessment and for algorithm and application improvements (Hou, 2005).

The complexity of mounting a comprehensive ground validation program was an important lesson learned from TRMM (see Chapter 2). Because GPM algorithms must account for more variable seasonal and geographical conditions as well as the different members of the constellation, the ground validation program will be even more complex than for TRMM. A global distribution of cooperative international sites that provide ground measurements for calibration is required to assess the effects of variations in precipitation types and processes associated with topographic, latitudinal, and seasonal effects (Flaming, 2004). In addition, GPM validation will need to be viewed in the larger context of validation and integration of information from a variety of spaceborne observing platforms with ground-based measurements, data assimilation, and modeling efforts (see Box 4.1).

A broad range of ground validation activities is under consideration.[4] For example, three types of ground validation sites are envisioned (Hou, 2005): (1) surface precipitation statistical validation sites for direct assessment of GPM satellite data products over larger scales, (2) precipitation process sites for improving understanding and modeling of precipitation physics in physical and radiance spaces for satellite retrieval algorithm evaluation and improvement, and (3) integrated hydrological sites for advancing hydrological applications.

Targets for validation include both satellite products and cloud-resolving models run for the location of the validation site. In addition to documenting the percentage of time that the algorithm or model meets specific accuracy criteria, validation information will likely be useful to understand success or failure based on observed meteorological conditions (Kummerow, 2006)—that is, the evaluation will provide a learning opportunity that ultimately leads to better spaceborne precipitation estimates.

NOAA can provide a wide range of observational assets for the ground validation research program that will improve the quality of precipitation products in the GPM era, with obvious return benefits to NOAA operations. These assets include observations from the national rain gauge, radar, and profiler networks (see Chapter 3); data from NOAA-supported special networks and projects (e.g., the climate reference network and the Hydrometeorological Testbed[5] [see Box 4.2, Figure 4.1, and Figure 4.2]). NOAA's contributions can also include upgrades of existing networks (e.g., the addition of dual polarization to the NEXRAD [Next Generation Radar] network—see Chapter 3).

The NOAA Observing Systems Architecture web site[6] includes links to an inventory of observing systems as well as requirements for observations. Maintainers of NOAA's networks and instruments, as well as NOAA scientists

[4]See *http://gpm.gsfc.nasa.gov* for the latest status.
[5]See the Hydrometeorological Testbed web site at *http://hmt.noaa.gov*.
[6]*http://www.nosa.noaa.gov*

BOX 4.1
A Vision of Integration and Validation for the GPM Era

A key goal for GPM is better integration of spaceborne and ground-based observations with data assimilation and numerical modeling efforts. Ultimately, the "best" precipitation product may result from a smart blending and assimilation of the observations with numerical models. Similarly, validation of the observed and/or derived precipitation estimates will have to be approached comprehensively, embracing every possible opportunity to evaluate different steps along the data-processing stream, and including temperature and humidity as well as dynamics information as a function of the scale that drives cloud and precipitation formation. This is conceptualized in Figure 4.1.

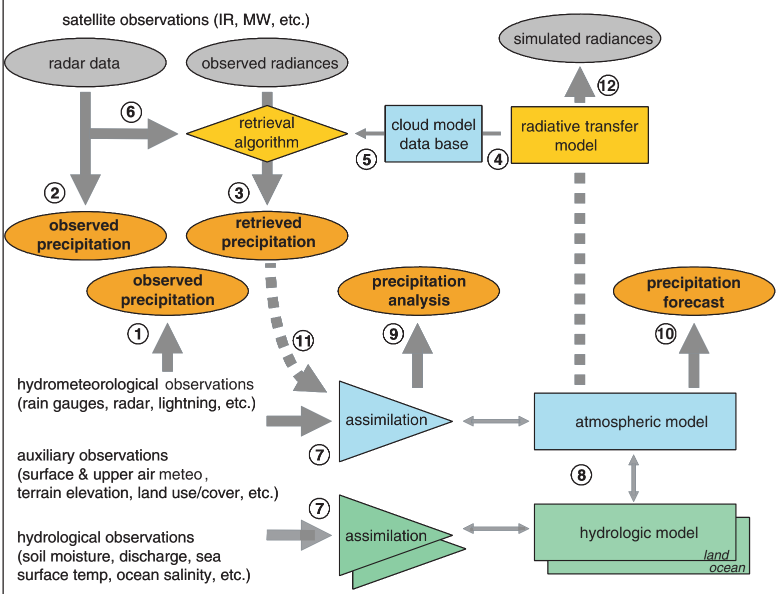

FIGURE 4.1 Conceptual visualization of GPM-era data integration and validation. The numbers provide links to the text. Dashed lines are used to indicate processes that will become more common in the near future, while double-ended arrows indicate two-way coupling. Drawing by M. Steiner, Princeton University.

who use the data in their research-and-development activities, can be productively involved in identifying potential ground validation sites and data sets that would be of value for algorithm development and validation.

Finding: **NOAA can provide a wide range of assets to assist GPM in mounting a comprehensive ground validation program over North**

The ground-based precipitation measurements (rain gauge, radar, lightning data, etc.) will be merged to generate "observed precipitation" products (encircled 1) that may be useful in their own right and provide a basis for comparison to precipitation estimates from spaceborne sensors (encircled 2 and 3). Active microwave sensors (i.e., radar) aboard the Tropical Rainfall Measuring Mission (TRMM) and the GPM core satellite yield more direct observations of precipitation (encircled 2) (e.g., Marzoug and Amayenc, 1991; Iguchi et al., 2000) than infrared and passive-microwave radiances that involve more complicated algorithms to obtain "retrieved precipitation" estimates (encircled 3), potentially requiring a radiative transfer model (encircled 4) and cloud model data base (encircled 5) and/or radar information (encircled 6), as outlined in Box 3.2. The ground-based precipitation measurements, complemented by a range of hydrological observations and auxiliary data, will be assimilated into NWP models (encircled 7) that are coupled to hydrologic (land-surface and ocean) models (encircled 8). This process yields "precipitation analyses" (encircled 9) and "precipitation forecasts" (encircled 10) (including measures of uncertainty) that are internally consistent with the observations and model physics. In the near future, cloud- and precipitation-affected satellite-observed radiances will be directly assimilated as well (encircled 11) (e.g., Weng and Liu, 2003; Andersson et al., 2005; Greenwald et al., 2005). Alternatively, based on the information provided by the coupled land surface-atmosphere models, top-of-the-atmosphere radiances can be computed by means of a forward radiative transfer model (encircled 12).

These processing streams provide many opportunities for diagnostic evaluation and feedback that will lead to improvements of retrieval algorithms, model physics, and data assimilation procedures alike. This evaluation may occur at the level of surface precipitation estimates (i.e., observed or analyzed versus retrieved) as well as top-of-the-atmosphere radiances (i.e., observed versus simulated brightness temperatures). While the former approach to "validation" has been the backbone during the TRMM era, the latter form of evaluation will be a key addition for GPM; will involve a detailed understanding of the microphysical processes; and will require appropriate four-dimensional dynamic, thermodynamic, and microphysical observations.

Most of the evaluation and feedback activities are being worked on by a variety of groups within NOAA, NASA, JCSDA, universities, and internationally. The challenge is to make these activities work in a coherent way toward the common goal of improved precipitation forecasts.

America. In addition to observational assets, NOAA can bring expertise in validation site selection, algorithm development, and modeling. Active participation in the GPM ground validation program will help the agency prepare for the GPM era. Operational centers can use data sooner if error characteristics are readily available

BOX 4.2
Hydrometeorological Testbed

There will be a symbiotic relationship between GPM and the Hydrometeorological Testbed. The Hydrometeorological Testbed will use GPM data as an additional input for experimentation and demonstration, and GPM will obtain validation elements from the Hydrometeorological Testbed. The Hydrometeorological Testbed concept aims to accelerate the infusion of new technologies, models, and scientific results from the research community into daily National Weather Service forecasting operations. The Hydrometeorological Testbed is conceived as a process in which ideas for improved products and services are demonstrated in a quasi-operational setting (Figure 4.2). If the experimental products or tools stand up to rigorous tests of usefulness, accuracy, reliability, computational efficiency, cost-effectiveness, and repeated close scrutiny by users, they can make the transition to operations. Otherwise, user feedback leads to modifications of the products and another round of evaluation or to elimination of the candidate tool or method.

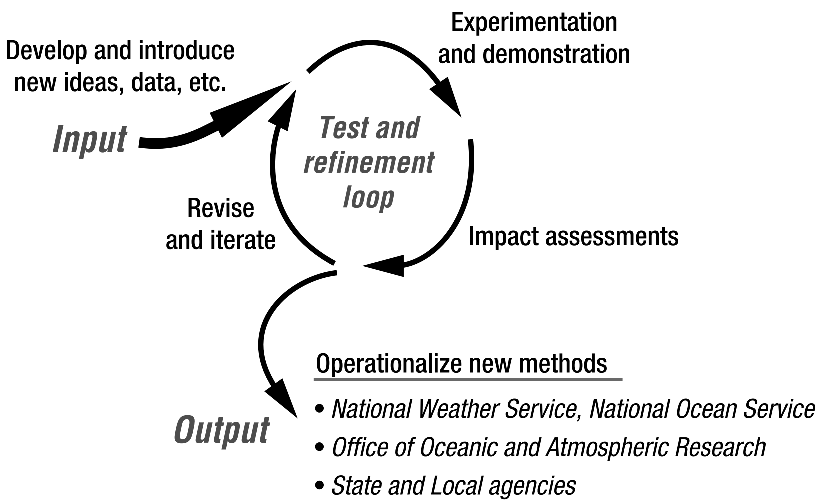

FIGURE 4.2 Conceptual design of the Hydrometeorological Testbed. Abbreviations are defined at the end of this report. SOURCE: Dabberdt et al., 2005. Reprinted with permission; copyright 2005.

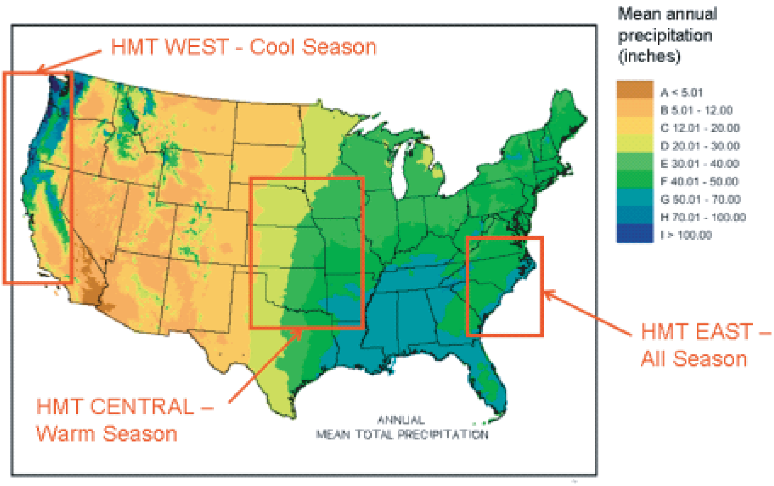

FIGURE 4.3 Regional focal areas for the Hydrometeorological Testbed. SOURCE: NOAA, 2006.

Unlike typical research field projects, the Hydrometeorological Testbed operates as a demonstration with forecasters and researchers joining forces in the operational setting. The first full-scale deployment of this highly instrumented facility, which targeted California's flood-vulnerable American River Basin, was completed in 2006. Two additional winter seasons are planned at this location. Following the California demonstration, Hydrometeorological Testbed facilities will be sequentially deployed to other regions of the United States (Figure 4.3) to address hydrometeorology problems that are unique to those locations. For example, the priorities of Hydrometeorological Testbed-West are on orographic effects, flooding, and water resources, while Hydrometeorological Testbed-East will focus on winter storms along the East Coast, with freezing rain, coastal cyclones (e.g., nor'easters), heavy snow, and lake-effect snow (Ralph et al., 2005). The project will run for a few years in each regional demonstration setting to determine its most useful new tools for improving precipitation and runoff forecasting methods. These successful tools will remain in place and will be duplicated (to the extent feasible) as the Hydrometeorological Testbed moves to the next region.

from the calibration-validation teams for radiances and retrieved variables.

Recommendation 4.2: **NOAA should explore ways of contributing observational assets and experience in site selection, modeling, and algorithm development to the GPM ground validation efforts. In addition, in partnership with NASA and other entities, NOAA should explore a comprehensive approach to international ground validation activities.**

5. Data Products

Once the calibrated and validated data from the GPM system become available, algorithm developers can use them to create derived products. This will eventually evolve into a real-time interface with data users. Whereas precipitation-related products can be patterned after those from ongoing efforts using remotely sensed data (see Chapter 3), a focus is needed on integrating GPM data with data from other satellite-based systems to provide a multisensor precipitation analysis (e.g., Box 3.2). From this analysis, hydrologic data assimilation products can also be derived. This will be facilitated by algorithm working groups within NOAA that are established well in advance of launch of the GPM core satellite. These groups, working closely with NASA counterparts, can engage in such efforts with available data sets (e.g., TRMM and Special Sensor Microwave/Imager [SSMI] data) as proxies until GPM core satellite data start flowing.

6. Archiving and Distributing Precipitation Data

Archives of historical meteorological data are an important component of precipitation research and applications. Archived data are needed for a variety of purposes, including tracking weather and climate trends, calibration of operational instruments, and long-term assessment of climate.

NOAA's National Climatic Data Center maintains climate records for NOAA historical data. As a World Data Center for Meteorology, the National Climatic Data Center also maintains many data sets from agencies around the world. This effort requires a number of steps, including acquisition, quality control, processing, summarization, dissemination, and preservation (NCDC, 2006), but securing resources to fund such an effort continues to be a challenge (NRC, 2006). The National Climatic Data Center may archive TRMM data as NOAA prepares for the GPM era; the National Climatic Data Center is engaged in discussions with NASA on this matter. Because TRMM is a NASA research mission, the raw data and processed products are currently archived in the NASA Distributed Active Archive Center at the Goddard Space Flight Center (NASA, 2006b).

***Finding*: TRMM data comprise a critical data set in the pre-launch phase of the GPM mission, and these data may be archived at NOAA's National Climatic Data Center. Archiving additional data sets such as those from TRMM and GPM will pose challenges for the National Climatic Data Center.**

***Recommendation 4.3*: As part of NOAA's strategic plan for GPM, NOAA should develop strategies for meeting its archiving needs in preparation for and during the GPM era.**

7. Infusion of New Technology

The timely infusion of new technology into the operational environment is a necessary focus if NOAA is to remain competitive in delivering the best observations, forecasts, and reanalysis products to users in the GPM era. This includes infusion of technological advances in hardware (e.g., observing capability, data processing and distribution) and software (e.g., algorithms for retrieval, blending or assimilation of data, model physics).

Multipartner testbeds such as the Hydrometeorological Testbed (Box. 4.2) or JCSDA (Box 4.3) provide one potential vehicle for exploring and exploiting new technology. In such testbeds, real-time models and data assimilation systems that maximize the use of new observations (e.g., from the GPM constellation) could be developed and tested. Other potential benefits of testbeds include facilitating interactions among the observation, modeling, and data assimilation communities, both within NOAA and more broadly with other agencies and academia. In addition, testbeds offer a potential means of smoothing out cultural differences between the research and operational communities and facilitating a better understanding of participants' needs, requirements, and limitations.

8. Data Assimilation

The advanced instruments of current and planned satellite missions among NOAA, NASA, DOD, and international agencies can and will provide large volumes of data on atmospheric, oceanic, and land-surface conditions with unprecedented accuracy and spatial resolution. As discussed in Chapter 3, NWP forecasts are often sensitive to initial conditions in dynamically active areas with clouds and precipitation. Because these areas often have few conventional observations, satellite data assimilation is essential. Thus, significant advances in NWP forecast skill are expected through development of data assimilation systems that are better suited to handling precipitation, cloud, and soil moisture information. Typically, it takes 1-3 years to implement a new observation type into the operational data assimilation systems at NCEP and other NWP centers. For complex

BOX 4.3
Joint Center for Satellite Data Assimilation

The JCSDA (Figure 4.4) was founded in 2002 to foster and accelerate research and development of assimilation techniques to accommodate the rapidly growing space-based data streams and to serve as a vehicle for technology transfer to operations. As a joint, distributed center it engages units of NASA (Goddard Space Flight Center [GSFC], Global Modeling and Assimilation Office [GMAO]); NOAA (National Environmental Satellite, Data, and Information Service [NESDIS] Office of Research and Applications; Center for Satellite Applications and Research [STAR]; National Weather Service [NWS]; NCEP; Environmental Modeling Cen-

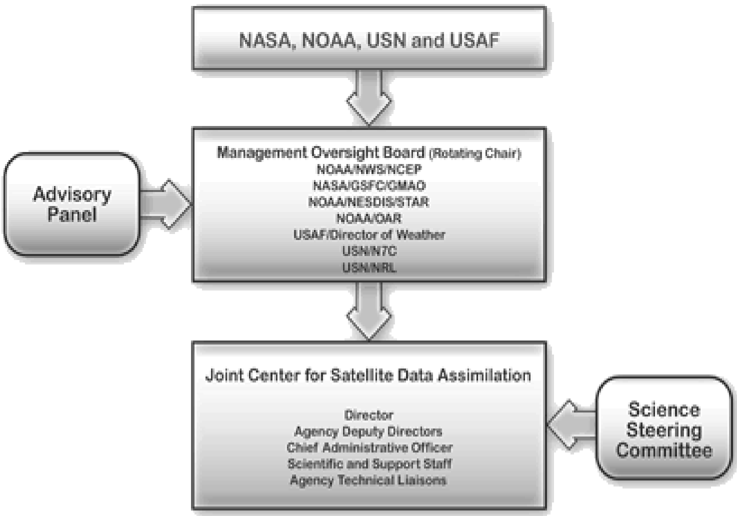

FIGURE 4.4 Schematic of the JCSDA. SOURCE: JCSDA, 2006. See Appendix E for definitions of acronyms.

types of observations such as precipitation, the time frame is longer. JCSDA (Box 4.3 and Figure 4.4) is at the forefront of U.S. advances in data assimilation and will be a vital resource for NOAA as it prepares to assimilate data in the GPM era.[7]

A range of effort will be necessary with respect to assimilation. Initially, analyses will be needed to evaluate the requirements of the next-generation,

[7]See the JCSDA web site at *http://www.jcsda.noaa.gov*.

ter; Office of Oceanic and Atmospheric Research [OAR]); the U.S. Navy (USN) (Oceanographer of the Navy [N7C] and Office of Naval Research, Naval Research Laboratory [NRL]); and the U.S. Air Force (USAF) (Air Force Director of Weather, Air Force Weather Agency). The National Science Foundation is affiliated with JCSDA through the University Corporation for Atmospheric Research and supports a visiting scientist program on Global Positioning System/Radio Occultation (GPS/RO).

JCSDA activities are divided into infrastructure development and proposal-driven scientific projects. Infrastructure development focuses on development and maintenance of a scientific backbone for JCSDA, whereas proposal-driven scientific projects are the primary mechanism for accelerating the transition of research and technological advances in remote sensing and data assimilation into the operational and product-driven weather and climate prediction environment.

These activities have yielded assimilation techniques for NASA's Atmospheric Infrared Sounder (AIRS), SSMI radiances, and GPS/RO measurements. In addition, a physically based retrieval method for sea surface temperature and a Special Sensor Microwave Imager/Sounder (SSMIS) radiance pre-processor have been developed. Along with providing monetary support for research projects, JCSDA has sponsored several workshops pertaining to satellite data assimilation, including ones focusing on GPS/RO, SSMIS, and cloud and precipitation assimilation.

The assimilation of precipitation and cloud information is one of six priority research areas identified by JCSDA management for the proposal-driven scientific projects. Topics of particular interest within this research area include

- assimilation of radiances in cloudy and precipitating areas,
- specification of observation error and forward model covariance statistics under a variety of cloud and precipitation conditions, and
- definition of background error covariance statistics for various cloud mixing ratios predicted by cloud prognostic schemes and cumulus parameterization schemes.

In addition to handling data from satellite instruments, JCSDA is also tasked to prepare for assimilation of new data sources as they become operational. However, JCSDA's ability to keep up with rapidly growing data streams is limited by its resources.

four-dimensional variational (or ensemble) data assimilation systems, taking into account the required computational and scientific personnel resources. Careful consideration will be necessary for constraining the variational assimilation using derivatives of observations, such as cloud and rain type, particle size distributions, and height of the melting layer or cloud top, among others. Significant forecast skill advances may also come from other improvements, including making full use of all channels over land (presently hampered by inadequate knowledge of the surface emission), and include higher frequencies (e.g., 165 and 183 GHz) over oceans (particularly for higher latitudes, winters, and situations when precipitation rates are low and precipitation is in the form of snow, cold drizzle, and sleet), refinements to the radiative transfer models used in assimilation (scattering by precipitation), and better characterization of background, model, and observational errors. Moreover, continued effort will be needed toward developing a global combined land-atmosphere-ocean assimilation system. Advances in assimilation will also be dependent on improvements in the treatment of moist physics in numerical models (see the following section).

It will be beneficial for data assimilation experts to become active members of sensor design and calibration-validation teams for future precipitation missions. From the perspective of benefits to assimilation efforts from such involvement, operational centers can use data sooner if error characteristics are readily available from the calibration-validation teams for radiances and retrieved variables. These errors include measurement errors, calibration errors or anomalies, and radiative transfer model errors. These errors are most useful for data assimilation if the error estimate includes information about the error probability distribution (i.e., the mean, standard deviation, and any relevant higher-order moments of the distribution).

Further mutual benefits will arise from coordinated efforts, knowledge, and sharing resources among data assimilation experts, satellite precipitation algorithm developers, and scientists involved in large interrelated projects (e.g., GEWEX [Global Energy and Water Cycle Experiment] and World Climate Research Programme) because of the availability of in situ observational data for validating the products and systems.

Finding: **Given the lead time required to bring new precipitation data into operational assimilation schemes and given the potential gains in forecast skill from doing so, NOAA can begin preparing now for assimilating data in the GPM era to ensure that its operational forecast models, forecasters, and product users are ready for GPM data as soon as possible after launch of the GPM core satellite. The existing microwave imagers in orbit are either similar or identical to those that will be flown with GPM; only the GPM core satellite with its dual-frequency precipitation radar instrument is not available (although TRMM has a single-frequency precipitation radar). These instruments can be used to develop assimilation methods and to improve model physical parameterizations in preparation for the GPM mission.**

Recommendation 4.4: **NOAA should immediately enhance research and development on data assimilation, model or observation error characterization, and moist physics parameterizations in models using proxy data from TRMM to test their performance.**

Finding: **Assimilation schemes for using GPM data will benefit in particular from focused efforts on (1) making full use of all channels over land through better characterization of the surface emission, including higher frequencies (e.g., 165 and 183 GHz) over oceans; and (2) radiative transfer models, which can be tested using data sets that combine satellite data from the present GPM-like constellation and in situ data, as in the case of collaborative missions such as CloudSat.**

Recommendation 4.5: **NOAA should direct special effort to (1) making full use of all channels over land through better characterization of the surface emission, including higher frequencies (e.g., 165 and 183 GHz), and (2) constructing high-quality satellite and in situ data sets to fully assess radiative transfer model performance.**

Finding: **The collaborative activities at JCSDA are an example of a successful partnership between NOAA and NASA. JCSDA provides an interface between research and operations, thereby offering a potentially effective mechanism for accelerating the use of research data in operations. JCSDA is well positioned to invigorate and advance research on assimilating satellite data.**

Recommendation 4.6: **NOAA should strengthen and coordinate its support of JCSDA efforts on precipitation assimilation through the establishment of a NOAA steering group on space-based precipitation missions, as suggested in Recommendation 4.1 above.**

Finding: **U.S. and international data assimilation scientists and operational NWP centers benefit mutually in terms of shared interests, knowledge, and resources from joint engagement in sensor design and calibration-validation teams and through collaboration with algorithm developers and personnel from large, interrelated projects (e.g., GEWEX and the World Climate Research Programme).**

Recommendation 4.7: **NOAA should support participation of its data assimilation scientists on sensor design and calibration-validation teams. In addition, NOAA should encourage collaboration among U.S. and international assimilation scientists, precipitation algorithm developers, and personnel involved in large interrelated projects.**

9. Model Physics Development

Contemporaneous advances in model microphysics and assimilation of moisture information are crucial to maximize the value of high-quality precipitation data (Recommendation 4.3). Significant progress will be possible only if the model physics are capable of handling data inputs in an internally consistent way. Otherwise, models will tend to reject the assimilated information. In addition to advances in the physics, questions remain about the trade-off between increased spatial resolution and the complexity of the microphysics scheme (e.g., bulk versus explicit formulation, number of cloud and precipitation particle categories).

10. Data Impact Evaluation

Comprehensive evaluation and diagnostic tools are cornerstones for advancing data assimilation and numerical model physics schemes as NOAA prepares for the GPM era. For example, simulated multispectral radiances can be evaluated against measured visible, infrared, and passive or active microwave satellite observations (Recommendations 4.3 and 4.4; Box 4.1).

Use of all data sources in such evaluations is valuable wherever and whenever possible. For example, data from TRMM's single-frequency Precipitation Radar (and the dual-frequency Precipitation Radar during the GPM era), which provides unique information about the vertical structure of precipitation throughout the troposphere, are invaluable in diagnosing whether a model is capable of generating reasonable vertical moisture distributions within precipitating systems.

Observing System Simulation Experiments allow quantification of the relative contribution of single observation types to NWP model forecast skill. Using GPM as an example, these experiments require a data assimilation system that is capable of assimilating rainfall observations so that different configurations of observing systems with and without rainfall observations can be compared. If several existing satellites provide similar observations (e.g., SSMI, SSMIS, the TRMM Microwave Imager, and the Advanced Microwave Scanning Radiometer for the Earth Observing System [AMSR-E]), the impact can also be evaluated as a function of spatial or temporal data coverage.

Observing System Simulation Experiments will facilitate assessments of the sensitivity of a model's forecast skill to GPM observations. In addition, Observing System Simulation Experiments can demonstrate the impact of adding spaceborne platforms and combinations of sensors in specific orbits and thereby provide important feedback for overall observing system design (Bauer et al., 2006b). In another approach, evaluating the propagation of observational uncertainties and errors through atmospheric and hydrologic models is key to providing accurate information for the end user and also to assess the potential for future improvements in model physics, retrieval, or observational capabilities. The Pilot Evaluation of High-Resolution Precipitation Products is an example of a "grassroots" effort in data impact evaluation. Presently, this effort relies on volunteers.

11. User Education and Training

User education, training, and feedback will be an important component in the success of the GPM mission. In the years leading up to the GPM launch, user conferences hosted by NOAA and NASA could help familiarize and educate potential users with the types of data and products that will become available. These conferences could continue through the post-launch and NOAA control phases, providing a vehicle for useful feedback from the community. NOAA has already set a precedent for such user conferences: the GOES-R program office has been holding such conferences for several years. These conferences aim to educate potential users about GOES-R and also to gain early feedback from the community on potential products, coverage, frequency, and resolution. In this regard, the user conferences are held with the goal of infusing user requirements into the design, operation, and implementation of GOES-R services.

SUMMARY

NOAA's partnership with NASA for the GPM mission is essential to ensure that NOAA's operational forecast models, forecasters, and product users are ready for GPM data as soon as possible after launch of the GPM core satellite. Joint NOAA-NASA activities are already under way, and increased NOAA support for these activities is needed to effectively engage in GPM planning. In addition, NOAA can start preparing for GPM now within the agency to make best use of the time available before launch of the GPM core satellite. NOAA's preparation activities are framed in Chapter 5 within the context of a three-phase strategic plan for GPM.

5

NOAA Roadmap to Prepare for Future Space-Based Global Precipitation Missions

The National Oceanic and Atmospheric Administration (NOAA) will play a significant role in the Global Precipitation Measurement (GPM) mission and the GPM follow-on mission. The committee recommends a three-phase strategic plan to formalize NOAA's preparations for the GPM mission and recommends a steering group for coordinating partnership activities and overseeing the implementation of the GPM strategic plan (Recommendations 2.1 and 4.1). This chapter presents a model for NOAA's GPM strategic plan. Next, NOAA's activities for the strategic plan are listed in the context of the three phases of the GPM mission (pre-launch, post-launch, and potential NOAA takeover phases). Then, the committee offers a recommendation for NOAA's role in the transition of the GPM mission from research to operations. Finally, five challenges for future space-based precipitation measuring missions are discussed.

GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE-R RISK REDUCTION PLAN AS A MODEL FOR NOAA'S GPM STRATEGIC PLAN

NOAA's strategic plan for GPM could draw from the NOAA Geostationary Operational Environmental Satellite-R (GOES-R) Risk Reduction Plan. Even though GOES-R will not be launched until 2012-2015 (similar to the time frame for launch of the GPM core satellite), NOAA has developed research funding instruments and supported efforts to reduce post-launch risk.[1] For example, fund-

[1]See "The NOAA GOES-R Risk Reduction Plan," unpublished document, P. Menzel (NOAA), 2006.

ing has been set aside for NOAA research offices and cooperative institutes to create simulated GOES-R data sets as proxies for algorithm testing and development by an Algorithm Working Group. These preparations serve two purposes: (1) they reduce the risk of not being ready to use data once GOES-R is launched and fully functional, and (2) they provide industry developing the GOES-R instruments with state-of-the-art software and algorithms to derive products from the data once these begin flowing. Collectively, these efforts should ensure a quick and effective transition to operations.

Finding: **The GOES-R Risk Reduction Plan could serve as a model for many elements of NOAA's preparations for the GPM mission.**

Recommendation 5.1: **NOAA should consider the GOES-R strategic readiness approach as a model for aspects of its GPM strategic plan.**

ACTIVITIES WITHIN THE CONTEXT OF THE THREE-PHASE NOAA STRATEGIC PLAN FOR GPM

Recommendation 2.1 emphasizes both intra- and interagency strategic planning. Of the activities recommended earlier in this report, examples of interagency activities include the following:

- Formalizing and supporting existing coordinating mechanisms between the National Aeronautics and Space Administration (NASA) and NOAA and establishing new mechanisms as needed
- Implementing an efficient NOAA-NASA interface for data producer and user feedback, quality assessment, operational readiness, and product distribution
- Assigning and supporting GPM readiness as a priority effort at the Joint Center for Satellite Data Assimilation (JCSDA)
- Developing a strategy for participation in the GPM validation and calibration effort
- Strengthening partnerships with international agencies (e.g., European Space Agency, Japan Meteorological Agency, World Climate Research Program) and international science working groups (e.g., the International Precipitation Working Group [IPWG])

Examples of recommended intraagency activities include the following:

- Formalizing a NOAA steering group (as successor to NOAA's ad hoc working group) to provide internal NOAA communication and coordination, help develop user requirements, set up data management, participate in interagency partnership activities, and ensure readiness of prototype data and product algorithms for smooth transition into NOAA operations

- Continuing to develop the NOAA data and product requirements from the GPM post-processing system

The main thrust of Recommendation 2.1 is the three phases of effort. For each of these three phases, activities can be differentiated by whether they are participation and initiation activities or planning and preparatory activities (Table 5.1). In addition to the concepts and actions that NOAA has already expressed interest in pursuing (e.g., GPM follow-on activities), the committee has recommended additional, detailed guidance for activities in preparation for the GPM mission. NOAA will need to start as soon as possible with its GPM preparations during the pre-launch phase.

RESEARCH-TO-OPERATIONS IMPLEMENTATION PLAN

Beginning during the pre-launch phase and continuing throughout the post-launch phase, NOAA will have to develop a comprehensive implementation plan for the transition of GPM from a research mission to an operational mission as part of its three-phase strategic plan. The implementation plan will need to be designed to ensure continued acquisition and application of high-quality, intercalibrated global satellite-based precipitation observations in support of NOAA's mission-oriented forecasting operations and climate services. To accomplish this, operational versions of the four basic components of the GPM research program (see Chapter 1) will be needed and budget planning will have to begin during the GPM post-launch phase.

1. GPM Core Satellite and Constellation Satellites

The array of satellites required for operational global precipitation measurement and mapping can be viewed in an international context as a major component of the World Weather Watch Global Observing System and the Global Earth Observation System of Systems. International collaboration and NOAA leadership are essential to maintain the constellation of GPM satellites since no nation can fully fund the total operational system. Consequently, the operational strategy for such a constellation will have to account for the international aspects of the program and the continually evolving mix of sensors.[2] The GPM concept can accommodate these international and uncertain aspects as long as the GPM data structure is flexible and there is a common baseline for intercalibration of sensors (i.e., the GPM core satellite radiometer) (Kummerow, 2006).

[2]The committee made a number of recommendations in Chapter 3 that relate to the constellation.

TABLE 5.1 Proposed NOAA Activities During Pre-launch, Post-launch, and Potential NOAA-Takeover Phases of the GPM Mission

Phase	Category of Activity	Action
Pre-launch	Initiation and participation	• **Formally support the NOAA-NASA GPM Research and Operations Group, the NASA Precipitation Measurement Missions science team, JCSDA, and IPWG through the establishment of a NOAA steering group on space-based precipitation missions, through direct support of these partnership activities, and/or through support of individual NOAA scientists. The NOAA steering group on space-based precipitation missions should serve as a focal point at NOAA to coordinate GPM partnership activities with NASA and should oversee the implementation of the GPM strategic plan recommended by this committee. (4.1)**[a]
		• **Formally support contributions of NOAA scientists to the IPWG so that NOAA's GPM program will help lead the IPWG to the next generation. NOAA should fully fund its IPWG collaborations and ensure that its multi-sensor precipitation techniques result in state-of-the-art operational rain rate algorithms. (3.6)**
		• **Support precipitation assimilation work through JCSDA. (4.6)**
		• **Enhance research and development on data assimilation and moist physics parameterizations in models using proxy data from TRMM to test performance. (4.4)**
		• **Make full use of all microwave channels through better characterization of the surface emission, including higher frequencies over oceans (e.g., 165 and 183 GHz). Construct high-quality satellite and in situ data sets to fully assess radiative transfer model performance. (4.5)**
		• **Support participation of NOAA data assimilation scientists on sensor design and calibration-validation teams. In addition, encourage collaboration among assimilation scientists, precipitation algorithm developers, and personnel involved in large inter-related projects. (4.7)**

continued

TABLE 5.1 Continued

Phase	Category of Activity	Action
		• **Develop strategies for meeting the archiving needs of the GPM era. (4.3)** • **Communicate to the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program office the critical role the NPOESS microwave imager will play in NOAA's GPM and GEOSS efforts. NOAA's strategic plan for GPM should include NPOESS contingency plans. (3.3)** • **Use NOAA's influence to facilitate free and swift access to all microwave imager digital data sets, whether they be from U.S. missions or foreign satellites. NOAA should use its international influence to encourage foreign collaborators in order to create a robust microwave satellite constellation. (3.4)** • **Take a leadership role in the international satellite community by proposing specific actions for the accurate calibration of all microwave imagers and sounders through cross-calibration and standard reference data sets and for implementing *internal* calibrations on all future microwave sensors. (3.5)** • **Strengthen rain gauge and radar networks and integrate the data into GPM calibration and validation efforts. (3.1, 3.2)** • **Explore ways of contributing observational assets and experience in site selection, modeling, and algorithm development to the GPM ground validation efforts. In addition, and in partnership with NASA and other entities, explore a comprehensive approach to international ground validation activities. (4.2)** • Develop research partnerships and support universities to fully exploit the developing ability to infer precipitation and associated physical and dynamical processes from space-based observations. (Chapter 3) • Host (with NASA) user conferences to familiarize

TABLE 5.1 Continued

Phase	Category of Activity	Action
		and educate potential customers on the types of data and products that will become available. (Chapter 4)
	Planning and preparatory	• **Formalize GPM planning by developing a comprehensive, coordinated, agency-wide strategic plan for activities in all three phases of the GPM mission (including a plan for the transition of GPM from a research program to an operational system[b]). Determine, with NASA, each agency's respective roles and responsibilities in all three phases. (2.1)**
		• **Consider the GOES-R strategic readiness approach as a model for aspects of the NOAA GPM plan. (5.1)**
		• Begin to develop the infrastructure and throughput requirements for the real-time receipt of data at the ingest port to NOAA computers and the product development interface. (Chapter 4)
		• Properly support product development activities so algorithm testing and advancement can occur by the launch of the GPM core satellite. (Chapter 4)
		• Plan for building up NOAA computing capacity so it is ready when needed. (Chapter 4)
Post-launch	Initiation and participation	• Develop full awareness of GPM data characteristics. (Chapter 4)
		• Receive GPM data in real time. (Chapter 4)
		• Evaluate the potential for assimilation and model improvements to handle GPM data and implement those that have potential to improve the value of the data, including computer processing power needs and data storage capacity for the operational phase. (Chapter 4)
		• Host (with NASA) enhanced algorithms and user conferences to promote user education, training, and feedback. (Chapter 4)

continued

TABLE 5.1 Continued

Phase	Category of Activity	Action
	Planning and preparatory	• **Develop a follow-on NOAA program for the time after GPM ends and prepare to lead building this constellation; view U.S. contributions as components of a continuing and evolving international constellation of satellites; pursue efforts within the World Meteorological Organization and the Coordination Group for Meteorological Satellites to strengthen support for an operational program of satellite-based global precipitation measurements.[c] (5.2)** • Establish budget requests for operating the satellite(s) so that resources are in place for the potential NOAA takeover phase. (Chapter 5)
Potential NOAA takeover	Initiation and participation	• Operate the GPM core satellite and U.S. satellite contributions to the constellation. (Chapter 5) • Process data in real time and deliver products to the operational and research user community. (Chapter 5) • Use error characterization for retrieval algorithms and data assimilation applications from the GPM ground validation program. (Chapter 2) • Begin building the GPM follow-on operational system. (Chapter 5) • Implement the follow-on operational constellation near the end of this phase. (Chapter 5)

NOTE: These activities are discussed in Chapters 3, 4, and 5 of this report; activities associated with a specific committee recommendation are listed in boldface type.

[a]Each recommendation in the chapters of this report is assigned a reference number. The first digit of the reference number corresponds to the chapter in which the recommendation appears (Chapter 2, 3, 4, or 5). The second digit of the reference number corresponds to the sequential order in which the recommendation appears within its chapter.

[b]Discussed in more detail in next section.

[c]Discussed in the final section.

2. Continuation of an Intercalibration Program

Since it now seems likely that the Global Space-Based Inter-Calibration System (GSICS) will be implemented long before launch of the GPM core satellite (see Chapter 3), links will develop during the GPM post-launch phase between the GSICS operational system and the GPM research intercalibration program that includes operational satellites. This intercalibration system will have to continue through the GPM operational mission.

3. Continuation and Expansion of an International Ground Validation Program

Continuation and expansion of a ground validation program is essential for acquisition of high-quality, intercalibrated, and validated precipitation data from the operational constellation. An effective global ground validation program requires a high degree of international cooperation as well as substantial resources. The NOAA data and observational contributions to the GPM ground validation program (Chapter 3) will have to be developed with due consideration for possible long-term use as assets for an operational program.

4. Development of a Suite of Data and Data Products

The GPM operational mission would generate precipitation data and data products to meet agency operational needs and those of national and international customers. These products would be the operational equivalent of the research products from the GPM Precipitation Processing System, including intercalibrated radiances for model assimilation and timely high-resolution global and regional precipitation analyses (e.g., the NOAA Climate Prediction Center morphing technique [CMORPH] product [see Chapter 3]).

> *Finding:* **The transition of GPM from a research program to an operational system will have to be designed to ensure continued acquisition and application of high-quality, intercalibrated global satellite-based precipitation observations in support of NOAA's mission-oriented forecasting operations and climate services. This will involve four areas of effort: (1) GPM core satellite and constellation satellites, (2) continuation of an intercalibration program, (3) continuation and expansion of an international ground validation program, and (4) development of a suite of data and data products.**

> *Recommendation 5.2:* **NOAA's strategic planning for GPM should address the need for the development and implementation of opera-**

tional versions of the four basic components of the GPM research program.

POST-GPM OPERATIONAL PRECIPITATION SYSTEM

NOAA has presented the concept of an operational follow-on to GPM (Dittberner, 2006). Planning for such a system will have to be initiated during the post-launch phase of GPM (Table 5.1). Among many details, these plans will need to consider how to exploit developments that enhance the ability to measure rainfall from space and mitigate deficiencies in the GPM observational system. Five such challenges are described below.

1. Measuring Light Precipitation in Mid- and High Latitudes

There remain key gaps in the current GPM plans for measurement of global precipitation. One shortfall is in measurement of light precipitation in mid- and high latitudes. The GPM radar has questionable sensitivity for detection of light rain, thus, its value for validating passive microwave precipitation estimates of light precipitation is uncertain. The European GPM (EGPM) mission concept was aimed at addressing this measurement gap, but it appears that this mission will not materialize.

2. Measuring Solid Precipitation

Satellite-based approaches for inferring solid precipitation are at an early stage of development, and observing strategies for advancing the measurement of solid precipitation have received little attention. Passive microwave methods are indirect and untested, and it remains unclear whether current and planned passive microwave measurements will overcome this deficiency. Compounded with the difficulty of measuring precipitation over land (see next section), estimating solid precipitation over mountains is of particular concern in many areas of the world where the population depends on snowmelt at high altitudes for fresh water.

3. Measuring Precipitation over Land

Problems remain in inferring precipitation over land from passive microwave observations. The methods remain largely empirical; although the use of spaceborne radar for training these passive methods is helpful, the lack of a direct physical basis for overland passive microwave rainfall is a source of ambiguity that will require additional information. The type of information best suited and available remains unresolved. One promising development is a study demonstrating that precipitation retrievals from passive microwave sounders over land are as good as (if not better than) scanning radiometers over land in the 1-10 mm per hour range (Hou, 2005; Bauer, 2005).

4. Spatial Resolution

A passive microwave sensor is being considered as a component on the next generation of operational geostationary sensor suites (GOES-R) using higher frequencies to partially mitigate spatial resolution issues. This would allow continuous passive microwave viewing of the life cycles of low- and midlatitude precipitation systems, would provide valuable information for filling the time-space gaps in passive microwave observations from polar orbiters, and would provide another valuable tool for intercalibration. However, low spatial resolution remains a challenge for any space-based precipitation-measuring mission.

5. Understanding Precipitation Processes

Advances in the understanding of precipitation processes (e.g., microphysics, the influence of aerosols) will likely contribute to the improvement of retrieval algorithms, which can be implemented for current precipitation retrievals and applied retrospectively to improve climate data records.

> ***Finding:*** **The array of satellites required for operational global precipitation measurement and mapping is best viewed in an international context and as a component of the World Weather Watch Global Observing System and the Global Earth Observation System of Systems. In this context, NOAA has proposed the concept of an operational constellation that will follow GPM.**

> ***Recommendation 5.3:*** **NOAA's planning for an operational follow-on to GPM should begin during the post-launch phase of GPM and should view U.S. contributions as a component of a continuing and evolving international constellation of satellites. In addition, NOAA should pursue efforts within the World Meteorological Organization and the Coordination Group for Meteorological Satellites to strengthen support for an operational program of a global, satellite-based precipitation measurement system.**

SUMMARY

Although the future state of operational global precipitation measurements is unclear, NOAA has the opportunity to lead and catalyze development of an operational precipitation measurement network in addition to supporting and working on the next-generation observational efforts that are planned for the

GPM mission. NOAA's resources could be directed at many activities that will help in this regard (Table 5.1), and the present constellation of passive microwave sensors in conjunction with TRMM's unique suite of sensors provides an ideal source of global, intercalibrated data with which to refine operational applications in preparation for future precipitation-measuring missions.

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Appendixes

A

NOAA White Paper: NOAA Cooperation with NASA on the Global Precipitation Mission

Co-authored by R. Ferraro, A. Gruber, G. Legg, J. Janowiak, K. Vincent, J. Gurka, B. Martner

The distribution of water and its change over time are two of the most critical issues facing the world's population. The single most destructive weather-water-climate hazard is flooding, which can result from heavy precipitation from either relatively short-lived "weather" phenomenon (e.g., severe storms, tropical cyclones) to relatively long-lived "climate" events (e.g., El Niño). Because these events occur throughout the world where U.S. interests may be affected, a system to monitor potential flooding hazards is important. NOAA is the sole federal agency that has the responsibility for issuing weather-water-climate warnings for the country. To support this function, NOAA develops and validates algorithms for the retrieval of precipitation rates from remotely sensed data and uses this information for flash flood forecasts, rainfall potential estimates, input into NWP models and climate monitoring. Additionally, NOAA serves the interests of other government agencies here (e.g., the Departments of Defense and State) and abroad by providing assessments of impending hazards

Furthermore accurate and regional precipitation measurements support all of NOAA's four overarching Strategic Goals:

1. Protect, restore, and manage the use of coastal and ocean resources through ecosystem management approaches.
2. Understand climate variability and change to enhance society's ability to plan and respond.
3. Serve society's needs for weather and water information.
4. Support the Nation's commerce with information for safe and efficient transportation.

NOAA believes that the Global Precipitation Measurement (GPM) Mission is a system that can assist NOAA in meeting its user and mission requirements and fulfilling its strategic goals. The GPM will be a resource that can greatly improve NOAA's primary mission, which is the protection of life and property by providing timely and accurate information on precipitation events worldwide. This of course is critical for accurate meteorological and hydrologic modeling and assessment. GPM will also serve as a prototype to help NOAA improve its current satellite capabilities and to better define the future operational precipitation measuring system from space. As a testimony to this, the Workshop on NOAA's Requirements for Global Precipitation Data (November 2001, Report issued May 30, 2002) identifies NOAA's involvement in GPM as two of its major recommendations. Specifically:

- "NOAA should become an active partner with NASA in the Global Precipitation Measurement Mission. This system will provide the global three hourly precipitation estimates required by the operational modeling centers. Furthermore, significant improvements in precipitation information for nowcasting, extreme precipitation events and flash floods will be achieved when geostationary data, gauges and radars are combined with GPM. Consideration should be given to the establishment of a science team or working group that would define NOAA's role in and relationship to GPM."

- "NOAA should sponsor a ground-validation super-site at location that will complement the super-sites that NASA will establish for GPM. These sites would include concentrations of quality precipitation gauges (such as those of NCDC's Climate Reference Network) and advanced ground-based remote sensors to measure precipitation, clouds, and water vapor independently of the over-flying satellite instruments."

In addition, NOAA should develop techniques for integrating GPM data into its operational precipitation analysis systems and for assimilating these analyses into weather, water and climate forecast models. These techniques should account for uncertainty in GPM products and for the propagation of this uncertainty by atmospheric and hydrological models.

Testbeds are a new concept in NOAA for accelerating the transfer of research technologies into operational use by the National Weather Service (NWS). The NWS Science and Technology Infusion Plan (STIP) of 2002 calls for the development of a regional and re-locatable Hydrometeorological Testbed (HMT) in which NOAA researchers join forces with NWS weather forecasters and River Forecast Center runoff forecasters to evaluate new precipitation observing and model tools in an operational setting. Once established, such an HMT could also readily serve as a NOAA base for additional GPM ground validations and would provide a direct link between the new GPM products and operational forecasting.

NOAA has scientific expertise in the retrieval of precipitation from satellites and their utilization for a number of applications, ground monitoring assets, and operational processing capabilities that would make it a unique partner with NASA in the GPM program. NOAA anticipates that the following assets will be available as part of its potential contribution to GPM:

A. Visible, IR, and microwave data from NOAA-operated satellites or satellite data that NOAA anticipates receiving in near real time based on prior data exchange agreements (which will include GOES, POES, DMSP, WindSat, NPOESS Preparatory Mission, and NPOESS).

B. Ongoing cooperative R&D activities with NASA that focus on the areas of precipitation retrieval from satellites and their applications (e.g., Global Precipitation Climatology Project, Joint Center for Satellite Data Assimilation, etc.)

C. GPM Science Team Members (through current/forthcoming NASA Research Opportunities and through a joint agreement with NASA) who possess expertise on:
   a. Rainfall retrieval algorithms (flash flood to climate scale) and associated validation/error modeling
   b. Radiative transfer, in particular, over land surfaces and at millimeter wavelengths
   c. Applications in support of a variety of NOAA missions (i.e., tropical cyclones, climate monitoring, etc.) carried out by centers such as the National Precipitation Prediction Unit (a joint NCEP-NESDIS activity), the Climate Prediction Center, and National Weather Service Forecast Offices and River Forecast Centers
   d. Use of satellite-derived rainfall in NWP models/assimilation techniques
   e. Calibration of satellite sensors
   f. Evaluation of satellite-derived precipitation estimates

D. Field calibration/validation assets:
   a. Climate Reference Network
   b. North American Monsoon Experiment (NAME) rain gauge network
   c. Research and operational radars and profilers, in particular, through the proposed Hydrometeorological Test Bed
   d. Aircraft-borne radiometers to support field campaigns
   e. PACRAIN rain gauge network

E. Hydrological Applications
   a. Multisensor precipitation analysis
   b. Ensemble precipitation analysis
   c. Uncertainty propagation through hydrologic models
   d. Hydrologic data assimilation
   e. Global hydrologic forecast applications

F. Data archival and operational distribution networks
   a. CLASS
   b. EMSNet node
   c. Operational File Server (CEMSCS)
   d. Dedicated networks and circuits for operational distribution to global customers, including all national forecast centers

As a more formal way to become partners on GPM, it is recommended that NOAA and NASA establish a new component to the existing Joint Center for Satellite Data Assimilation that will focus on precipitation measurements and applications. Ultimately, this center will encompass much of NOAA's precipitation-related activities. Through this center, NOAA will contribute resources to support NOAA Science Team members, a joint Research Announcement, joint field campaigns, and data processing/archival. To accomplish this, NOAA should incorporate the potential benefits of GPM within its ongoing Program Baseline Assessment (PBA) and Gap analysis. For example, a gap was recently identified within the Hydrology Program regarding the insufficient number of global precipitation observations. Clearly, GPM would help NOAA alleviate this gap. Through the PBA process, long-term funding for activities related to GPM can be secured. However, in the short term, NOAA should provide seed funds beginning in FY 04 to formalize its partnering commitment to NASA. Once this has been established, joint, national-based partnering meetings between NASA and NOAA should be held on a regular basis.

B

NOAA's Near-, Mid-, and Long-Term Goals

NOAA NEAR-TERM GOALS (2005-2010)

1. Data Processing/Algorithm Implementation:
   - NOAA should leverage off of NASA's effort on the Precipitation Processing System to develop a parallel joint NOAA-NASA precipitation processing system to be run at NOAA in near real time.
   - Develop a prototype global quantitative precipitation estimation (QPE) (merged satellite, radar and gauge) that can serve as a "day-1" analysis system when data from GPM become available. Utilize measurements from new networks such as NERON.

2. R&D:
   - Develop advanced multisensor retrieval algorithms, with emphasis on cold-season and orographic precipitation.
   - Provide accurate estimates of magnitude of global oceanic precipitation.

3. Instrumentation:
   - Perform GPM risk reduction activities by utilizing TRMM measurements.
   - Utilize testbeds to improve QPE via new instrumentation.
   - Develop advanced instrumentation to obtain accurate 3-D information and characteristics of precipitation from ground (e.g., polarmetric radars, profilers, disdrometers, etc.).

4. Applications - NWP (JCSDA):
   - Improve assimilation of radiances to produce accurate global moisture and precipitation fields in data assimilation.
   - Provide accurate precipitation estimates independent of the data assimilation system for validation and calibration.
   - Provide near-real-time accurate estimates of global precipitation over land for assimilation in land data assimilation.

NOAA MID-TERM GOALS (2010-2015)

1. Data Processing/Algorithm Implementation:
   - Parallel/joint PPS operated through joint facility similar to JCSDA.
   - Integration of in situ data (gauge, radar, other) into regional and global analysis.
   - Collect past measurements of precipitation and satellite radiances for as long as possible and process these to give as long, accurate, consistent records as possible.

2. R&D:
   - Continued development of advanced retrieval algorithms to include probabilistic QPE and utilization of cloud microphysics for NWP, flash flood, and climate.
   - Establish and carry out on-going reanalyses to produce extended and consistent historical records of precipitation.

3. Instrumentation:
   - Continued utilizations of testbeds.
   - Continue to support new technologies and organize into networks (e.g., WSR-88D upgrade to dual-polarization).
   - Utilization of GPM measurements along with advanced retrieval techniques to define future NOAA precipitation program/mission (GPM follow-on) and Geo-MW (GOES-R series).

4. Applications - Climate & NWP (JCSDA):
   - Direct assimilation of precipitation estimates in NWP.
   - Improve observed and modeled accuracy of tropical precipitation and distribution of latent heat release to improve hurricane, medium-range, monthly, and seasonal forecasts.
   - Improve forecasts of precipitation globally, with a short-range focus on the United States.

NOAA LONG-TERM GOALS (2015+)

1. Data production continues via joint GPM facility, including international partners.

2. NOAA-wide use of unified QPE.

3. Evaluate and improve mesoscale quantitative precipitation forecasts through new models capable of incorporating cloud-scale processes.
4. NOAA operational precipitation mission established—could be POES and/or GOES.

C

NASA Reauthorization Bill: NASA-NOAA Coordination

SEC. 306. COORDINATION WITH THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION.

(a) JOINT WORKING GROUP.-The Administrator and the Administrator of the National Oceanic and Atmospheric Administration shall appoint a Joint Working Group, which shall review and monitor missions of the two agencies to ensure maximum coordination in the design, operation, and transition of missions where appropriate.

The Joint Working Group shall also prepare the plans required by subsection (c).

(b) COORDINATION REPORT.-Not later than February 15 of each year, beginning with the first fiscal year after the date of enactment of this Act, the Administrator and the Administrator of the National Oceanic and Atmospheric Administration shall jointly transmit a report to the Committee on Science of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate on how the earth science programs of the National Oceanic and Atmospheric Administration and NASA will be coordinated during the fiscal year following the fiscal year in which the report is transmitted.

(c) COORDINATION OF TRANSITION PLANNING AND REPORTING.-

The Administrator, in conjunction with the Administrator of the National Oceanic and Atmospheric Administration and in consultation with other relevant agencies, shall evaluate relevant NASA science missions for their potential operational capabilities and shall prepare transition plans for the existing and future Earth observing systems found to have potential operational capabilities.

(d) LIMITATION.-The Administrator shall not transfer any NASA earth science mission or Earth observing system to the National Oceanic and Atmospheric Administration until the plan required under subsection (c) has been approved by the Administrator and the Administrator of the National Oceanic and Atmospheric Administration and until financial resources have been identified to support the transition or transfer in the President's budget request for the National Oceanic and Atmospheric Administration.

SOURCE: Johannes Loschnigg, Committee on Science, U.S. House of Representatives, 2005

D

Committee Biographies

Eugene M. Rasmusson (*Chair*) was formerly with the National Oceanic and Atmospheric Administration (NOAA) and is currently a research professor emeritus at the University of Maryland's Department of Meteorology. His general area of interest is the atmospheric general circulation and the global hydrologic cycle. Within this broad subject area he has focused on the nature and predictability of climate and hydrologic variability on time scales ranging from a few weeks to a few years. Much of his work has centered on the relationship between sea-air interaction in the tropics and global precipitation variability, with particular emphasis on the El Niño phenomenon of the tropical Pacific. He is interested in the nature and predictability of the various components of the hydrologic cycle over continental regions, particularly North America and as it relates to the understanding and prediction of seasonal precipitation anomalies (droughts, wet periods). The primary motivation for these interests is the development of methods for skillful seasonal prediction of climate variations and their effect on water resources. Dr. Rasmusson is a National Academy of Engineering (NAE) member. He has served on many National Research Council (NRC) boards and committees, including the recent Panel on Climate Change Feedbacks.

Nancy L. Baker is a meteorologist and head of the Data Assimilation Section, Marine Meteorology Division of the Naval Research Laboratory (NRL). She has worked for the Navy since 1985, and has extensive experience with data assimilation, observation quality control, global and mesoscale reanalysis and data impact studies, and observation adjoint sensitivity. Her implementation of satellite radiance observations for the Navy's global forecast model (NOGAPS) using NRL's 3D-VAR analysis (NAVDAS) produced significantly improved forecast skill. Dr. Baker is well respected in the data assimilation community, and serves as the technical liaison to the Joint Center for Satellite Data Assimilation (JCSDA) for the Navy. Dr. Baker leads several projects as the principal investigator, and collaborates with JCSDA partners and its international counterparts. She has published numerous journal articles and technical papers. In 2000, she received her Ph.D. in meteorology from the Naval Postgraduate School.

V. Chandrasekar is currently a professor at Colorado State University (CSU). Dr. Chandrasekar has been involved with research and development of weather radar systems for about 25 years. He has played a key role in developing the CSU-CHILL National Radar facility as one of the most advanced meteorological radar systems available for research, and continues to work actively with the CSU-CHILL radar supporting its research and education mission and is a co-principal investigator of the facility. He also serves as the deputy director of the newly established National Science Foundation (NSF) Engineering Research Center, Center for Collaborative Adaptive Sensing of the Atmosphere. Dr. Chandrasekar's current research funding includes National Aeronautics and Space Administration (NASA) support for precipitation research. He is an avid experimentalist conducting special experiments to collect in situ observations to verify the new techniques and technologies. Dr. Chandrasekar is coauthor of two textbooks, *Polarimetric and Doppler Weather Radar* (Cambridge University Press) and *Probability and Random Processes* (McGraw Hill). He has authored more than 100 journal articles and 150 conference publications and has served as academic adviser for over 40 graduate students. He served as a member of the NRC committee on Weather Radar Technology beyond NEXRAD (Next Generation Weather Radar), is the general chair for the 2006 International Geoscience and Remote Sensing Symposium, and has served on numerous review panels for various government agencies. He has received many awards, including the NASA technical achievement award, Abell Foundation Outstanding Researcher Award, University Deans Council Award, Outstanding Advisor Award, and the Distinguished Diversity Services Award. He was elected a fellow of the Institute of Electrical & Electronics Engineers (Geo-Science and Remote Sensing) in recognition of his contributions to quantitative remote sensing. He is also a fellow of the American Meteorological Society.

Carol Anne Clayson is an associate professor in the Department of Meteorology at Florida State University and is the director designate for the Geophysical Fluid Dynamics Institute. From 1995 to 2001 she was an assistant and associate professor in the Department of Earth and Atmospheric Sciences at Purdue University. Dr. Clayson's research interests are in air-sea interaction, ocean and atmosphere boundary layers, numerical ocean and coupled ocean-atmosphere modeling, and remote sensing of air-sea surface fluxes. She was the recipient in

2000 of a Presidential Early Career Award for Scientists and Engineers and an Office of Naval Research Young Investigator Award. She was also the recipient in 1996 of an NSF career award. Her professional service includes program chair for the 12th American Meteorological Society (AMS) Conference on Air-Sea Interactions in 2003 and membership on a number of committees and working groups, including the AMS Committee on Interaction of the Sea and Atmosphere; AMS Board of Meteorological and Oceanographic Education in Universities; NASA Tropical Rainfall Measuring Mission (TRMM) Science Team (until 2003); Tropical Oceans and Global Atmosphere Programme (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE) Air-Sea Flux Working Group; and the TOGA COARE Radiation Working Group. Dr. Clayson is a member of the AMS, American Geophysical Union (AGU), and Oceanography Society and of the NRC Board on Atmospheric Sciences and Climate.

Jeffrey D. Hawkins is the head of the Satellite Meteorological Applications Section at the Naval Research Laboratory's Marine Meteorology Division in Monterey, California. He earned his B.S. and M.S. degrees in meteorology at Florida State University. His research interests include mapping tropical cyclone structure and understanding multiple eyewall cycles using passive microwave remote sensing, incorporating aviation-related remote-sensing parameters to detect hazardous flying conditions, and transferring research efforts to operations. Mr. Hawkins received the AMS Special Act Award in January 2005, largely due to his tropical cyclone research efforts. Mr. Hawkins is a fellow of the AMS and has served as the chairman of the AMS Committee on Satellite Meteorology and Oceanography (2003), program chair for the January 2003 meeting, and short-course chair for Satellite Precipitation. Mr. Hawkins is an NRC postgraduate adviser and has served on the NRC Committee on Cooperation with the U.S.S.R. on Ocean Remote Sensing. He has 25 years of experience in satellite meteorology and oceanography (sea surface temperature, sea ice, and altimetry).

Kristina B. Katsaros is a former director of the Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, in Miami, Florida. She is currently an adjunct professor at the University of Miami's Rosenstiel School of Marine and Atmospheric Science, Applied Marine Physics Division, as well as an affiliate professor of atmospheric sciences at the University of Washington. Dr. Katsaros earned a Ph.D. from the University of Washington. She is a member of the NAE. Her research interests include processes of momentum, energy, and water transport between sea and air. Dr. Katsaros has used satellite data to estimate air-sea fluxes, including precipitation, and has attempted to understand the interaction of electromagnetic radiation (visible, infrared, and microwave) with waves on the sea surface. Using microwave radiometers and radars for analysis of midlatitude and tropical cyclones over the sea has dominated her research in the last decade.

M. Patrick McCormick is a professor of physics and a codirector of the Center for Atmospheric Sciences at Hampton University. For the past 38 years, Dr. McCormick has performed research on the development of sensors for measurements in Earth's atmosphere. This research has focused primarily on lidar and satellite limb extinction (occultation) techniques for characterization of aerosols, clouds, and other atmospheric species. For his undergraduate degree he majored in physics at Washington and Jefferson College in Washington, Pennsylvania. He received both his master's and his doctoral degrees in physics from the College of William and Mary. In his role as manager of the Center for Atmospheric Sciences, he has principal investigator duties for the Stratospheric Aerosol and Gas Experiment II and III, and co-principal investigator duties for satellite experiment CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), and conducts atmospheric research using satellite and supporting data. He has served on several NRC committees.

Matthias Steiner is a senior research scientist affiliated with the Department of Civil and Environmental Engineering at Princeton University. He received his Ph.D. in environmental sciences (with emphasis on atmospheric science) from the Swiss Federal Institute of Technology in Zurich. Dr. Steiner's research interests reach across hydrometeorology, cloud and precipitation physics, mountain meteorology, and radar and satellite meteorology. He is intrigued by the variability of precipitation in space and time and how to measure precipitation with in situ as well as remote-sensing instruments. His recent work is focused on understanding the effect of atmospheric moisture on the flow of air in and over complex terrain, and the associated cloud and precipitation processes. In addition, he has been investigating the uncertainty of satellite-based rainfall estimates and implications for hydrologic applications. Dr. Steiner served two terms on the AMS Committee on Radar Meteorology and just completed a 5-year term chairing the Technical Committee on Precipitation of the AGU Hydrology Section. He is a member of NASA's Precipitation Missions Science Team and of the National Science Foundation's Observing Facilities Advisory Panel. He served on the NRC Committee to Assess NEXRAD Flash Flood Forecasting Capabilities at Sulphur Mountain, California. Dr. Steiner was the recipient of the 2002 Editor's Award for the AMS *Journal of Hydrometeorology*.

Graeme L. Stephens is a professor in the Department of Atmospheric Science at Colorado State University. He received his Ph.D. in 1977 from the University of Melbourne. Dr. Stephens's research activities focus on atmospheric radiation and on the application of remote sensing in climate research, with particular emphasis on understanding the role of hydrological processes in climate change. His work has focused on understanding cloud radiation interactions as relevant to Earth's climate using both theory and numerical modeling as well as analysis of cloud properties from measurements made by satellites and aircraft. Dr. Stephens is currently the principal investigator of NASA's CloudSat Mission. His professional activities include being the editor of a number of leading atmospheric science journals and past chairman of the World Climate Research Program GEWEX (Global Energy and Water Cycle Experiment) Radiation Panel and the AMS Atmospheric Radiation Panel. He is a fellow of both the AGU and the AMS. Dr. Stephens is a former member of the NRC Board on Atmospheric Sciences and Climate, the Climate Research Committee, and the Committee on Earth Sciences.

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. Many of these products are derived from multispectral microwave sensors, including TRMM (as of now, TRMM is used indirectly). He served as a member of the U.S. Weather Research Project Science Steering Committee (1996-1999), the GOES (Geostationary Operational Environmental Satellites) Science Team (1996-1998), and the Geostationary Microwave Sounder Working Group (1995-1996). He is currently chair of the AMS Committee on Satellite Meteorology and has also been a member of the AMS Tropical Committee. In the last 5 years he has been honored by AMS with two awards and has published numerous papers. He served on the NRC Committee on NOAA NESDIS (National Environmental Satellite, Data, and Information Service) Transition from Research to Operations.

Ray A. Williamson is a research professor of space policy and international relations at the Space Policy Institute, George Washington University. Before joining the institute in 1995, Dr. Williamson served as a senior associate at the Office of Technology Assessment (OTA) of the U.S. Congress, where from 1979 to 1995 he directed most of OTA's space-related studies. At the institute his research focuses on policy analysis in several areas, including Earth observations, space transportation, and national security space. Dr. Williamson is a member of the International Editorial Board of *Space Policy*. He has served on the NRC Aeronautics and Space Engineering Board.

NRC Staff

Paul Cutler is a senior program officer for the Board on Earth Sciences and Resources of the National Academies. Before joining the Academies staff, he was an assistant scientist and lecturer in the Department of Geology and Geophysics at the University of Wisconsin, Madison. His research is in glaciology, hydrology, meteorology, and Quaternary science, and he has conducted fieldwork in Alaska, Antarctica, arctic Sweden, the Swiss Alps, Pakistan's Karakoram mountains, the midwestern United States, and the Canadian Rockies. Dr. Cutler received an M.Sc. in geography from the University of Toronto and a Ph.D. in geology from the University of Minnesota.

Rob Greenway has been a project assistant at the National Academies since 1998. He received his A.B. in English and his M.Ed. in English education from the University of Georgia.

Leah Probst is a research associate with the National Academies' Board on Atmospheric Sciences and Climate and the Polar Research Board. She received a B.A. in biology from George Washington University in Washington, D.C.

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Acronyms

4D-VAR	four-dimensional variational
AGU	American Geophysical Union
AIRS	Atmospheric Infrared Sounder
AMS	American Meteorological Society
AMSR-E	Advanced Microwave Scanning Radiometer for the Earth Observing System
AMSU-B	Advanced Microwave Sounding Unit
AQUA	satellite of NASA's Earth Observing System (EOS)
ASOS	automated surface observing system
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CHILL	National Radar Facility at Colorado State University
CloudSat	Cloud Satellite
CMIS	Conical Scanning Microwave Imager/Sounder
CMORPH	Climate Prediction Center Morphing Technique
COARE	Coupled Ocean-Atmosphere Response Experiment
CSA	Canadian Space Agency
DMSP	Defense Meteorological Satellite Program
DOD	U.S. Department of Defense
ECMWF	European Centre for Medium-range Weather Forecasts
EGPM	European Global Precipitation Measurement

ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FY	Fengyun (Chinese satellite series); fiscal year
GCOM	Global Change Observing Mission
GEOSS	Global Earth Observation System of Systems
GEWEX	Global Energy and Water Cycle Experiment
GIFTS	Atmospheric Soundings from Geostationary Orbit
GHz	gigahertz
GMI	GPM Microwave Imager
GMS	Geostationary Meteorological Satellite
GOES	Geostationary Operational Environmental Satellite
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Measurement
GPS/RO	Global Positioning System/Radio Occultation
GSFC	Goddard Space Flight Center
GSICS	Global Space-Based Inter-Calibration System
HADS	Hydrometeorological Automated Data System
HMT	Hydrometeorological Testbed
HWRF	Hurricane Weather Research and Forecasting
IEOS DEP	International Earth Observation System Data Exchange Principles
IFLOWS	Integrated Flood Observing and Warning System
INSAT	Indian National Satellite
IPWG	International Precipitation Working Group
IR	infrared
ISRO	Indian Space Research Organization
JAXA	Japan Aerospace Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JEA	Japan Environment Agency
JMA	Japan Meteorological Agency
JSC	Joint Scientific Committee
JWG	Joint Working Group
km	kilometer
LDAS	Land Data Assimiliation System
lidar	light detection and ranging

MADRAS	Microwave Analysis and Detection of Rain and Atmosphere Structure
Meteosat	Meteorological Satellite
METOP	Meteorological Operational satellite
MHS	Microwave Humidity Sensor
MITI	Ministry of International Trade and Industry of Japan
MOU	memorandum of understanding
MTSAT	Multi-Functional Transport Satellite
MW	microwave
MWRI	Microwave Radiation Imager
N7C	Oceanographer of the Navy
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NEXRAD	Next Generation Radar
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Mission
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
NWP	numerical weather prediction
NWS	National Weather Service
OAR	Office of Oceanic and Atmospheric Research (NOAA)
OTA	Office of Technology Assessment
PERSIANN	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
PMM	Precipitation Measurement Missions
POES	Polar-orbiting Operational Environmental Satellite
R-CLIPER	Rainfall CLImate and PERsistence
SCaMPR	Self-calibrating Multivariate Precipitation Retrieval
SSMI	Special Sensor Microwave/Imager

SSMIS	Special Sensor Microwave Imager/Sounder
STA	Japanese Science and Technology Agency
STAR	Center for Satellite Applications and Research (NOAA)
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
USAF	United States Air Force
USN	United States Navy
WindSat	Wind Satellite
WMO	World Meteorological Organization
WSR-88D	Weather Surveillance Radar-1988 Doppler