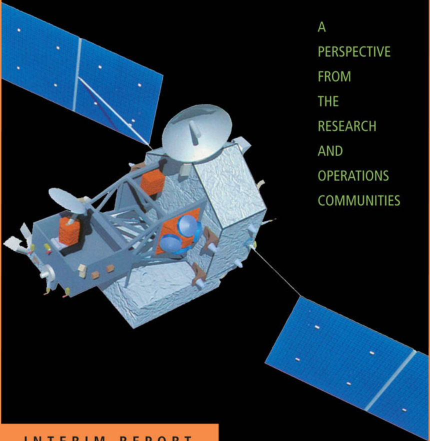
ASSESSMENT OF THE BENEFITS OF EXTENDING THE TROPICAL RAINFALL MEASURING MISSION

A PERSPECTIVE FROM THE RESEARCH AND OPERATIONS COMMUNITIES



INTERIM REPORT

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

ASSESSMENT OF THE BENEFITS OF EXTENDING THE TROPICAL RAINFALL MEASURING MISSION

A PERSPECTIVE FROM THE RESEARCH AND OPERATIONS COMMUNITIES

INTERIM REPORT

Committee on the Future of the Tropical Rainfall Measuring Mission

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

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Support for this project was provided by the National Aeronautics and Space Administration under Contract No. NASW-01001. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number 0-309-10282-0

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, D.C. 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

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Prologue

This report was originally released in December 2004 in prepublication form as the first report of a two-phase study to be carried out by the same committee. The first phase was sponsored by the National Aeronautics and Space Administration (NASA) and focused on the Tropical Rainfall Measuring Mission (TRMM). The second phase was sponsored by the National Oceanic and Atmospheric Administration and focused on the Global Precipitation Measurement mission. The report of the second phase will be published in a separate volume in 2006.

A number of significant decisions for TRMM have been made since December 2004. In 2005, NASA approved a waiver of its controlled reentry guidelines to allow TRMM to operate beyond the minimum fuel point required for a controlled reentry into Earth's atmosphere. In advance of the 2005 NASA Senior Review of 12 Earth science missions, NASA's TRMM team proposed to extend TRMM.[1] NASA's Goddard Space Flight Center was directed to continue TRMM science operations through fiscal year 2009, and TRMM may be further extended as a result of a future NASA Senior Review.

As of the publication of this report, the TRMM spacecraft and instruments are in excellent condition and are fully operational.[2] TRMM has enough fuel to operate until approximately 2012.

June 2006

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[1]The TRMM Senior Review Proposal is available online at http://trmm.gsfc.nasa.gov/trmm_rain/Events/TRMMSeniorProp_1.pdf [accessed May 11, 2006].

[2]As mentioned in Chapter 1, Box 1-1, the Clouds and Earth Radiant Energy System instrument failed shortly after launch. In 2002, one of the two Solar Array Drive Actuators lost sun-tracking function, leading to slightly less available power for the spacecraft but sufficient power for nominal operations of all working instruments. For up-to-date TRMM information and operational status, visit the mission Website at http://trmm.gsfc.nasa.gov.

Acknowledgments

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

Phillip Arkin, University of Maryland, College Park
Peter Bauer, European Centre for Medium-Range Weather Forecasts, Reading, Berkshire, UK
Russell Elsberry, Naval Postgraduate School, Monterey, California
Roger Pielke, Jr., University of Colorado/CIRES, Boulder
Amanda Preble, Naval Pacific Meteorology and Oceanography Center, Pearl Harbor, Hawaii
Roger Wakimoto, University of California, Los Angeles

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, and Carl Wunsch, Massachusetts Institute of Technology. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

The National Aeronautics and Space Administration (NASA), in cooperation with the Japan Aerospace Exploration Agency (JAXA), launched the Tropical Rainfall Measuring Mission (TRMM) in 1997. Designed as a minimum three-year mission with the goal of five years duration, TRMM has been collecting data for seven years, in large part due to the reliability of its sensors and the high quality of their measurements. Although initially intended as a purely research-oriented mission, TRMM now is used in operational applications such as hurricane forecasting because data from its suite of complementary sensors are unique and available in near real time. In the United States TRMM data are used operationally by the Joint Typhoon Warning Center, the National Center for Environmental Prediction, and the National Hurricane Center, among others. Internationally the data are used operationally by entities such as JAXA, the European Centre for Medium-Range Weather Forecasts, and the World Meteorological Organization tropical cyclone warning centers.

In July 2004 NASA announced that it would finally terminate TRMM in August 2004. At the request of the National Oceanic and Atmospheric Administration (NOAA), and with additional urging from others in the scientific and operational user community and the White House (see Appendixes E through H), NASA agreed to continue TRMM operations through the end of the hurricane season and until the end of 2004 (see Appendix I). But many users hope that the mission will be extended even longer, setting the stage for a difficult decision.

A further extension of TRMM beyond 2004 will pit financial constraints against the operational and scientific benefits of continuing; that is, are the benefits greater than the costs and can the necessary funds be secured? The scenario becomes more complicated if the mission is extended beyond late 2005. The TRMM spacecraft is sufficiently large that it will not burn up completely on reentry. Thus NASA will face a second decision point in roughly December 2005 when it must weigh in the element of the additional risk to life and property. For this second decision NASA must choose whether to (1) use TRMM's remaining fuel to conduct a controlled reentry into the atmosphere that directs the remains of the satellite into the ocean far from human settlements[1] or (2) continue TRMM operation until the fuel runs out in 2010 or 2011 and accept the added risk of an uncontrolled reentry because of the operational and scientific benefits of doing so.

THE ROLE OF THE NATIONAL ACADEMIES

In August 2004 NASA Administrator Sean O'Keefe requested that the National Academies provide advice on the anticipated scientific and operational contributions from extending TRMM beyond 2004. The charge to the Committee on the Future of the Tropical Rainfall Measuring Mission in the first phase of its work was to conduct a workshop and prepare an interim report to be delivered in December 2004 on how best to use the remaining TRMM spacecraft life. The Academies were able to begin the study process in October 2004, and immediately assembled the committee and planned an information-gathering workshop. The committee and workshop participants were asked to consider

- scientific and research contributions of TRMM to date and those expected if TRMM is continued;
- operational contributions of TRMM to date and those expected if TRMM is continued;
- assessment of expected benefits of continuing TRMM operation until (1) fuel is depleted to the level needed for a controlled reentry (around December 2005), and (2) all fuel is depleted (estimated to be 2010-2011).

A second phase of the committee's work will focus on needs for satellite-based measurements of tropical rainfall beyond TRMM (see Appendix B).

The committee hosted its phase I workshop in Washington, D.C., on November 8, 2004,[2] and subsequently drew on information and discussions from the meeting and other written inputs and information sources to address its task for phase I.

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[1]In this scenario controlled reentry would be in 2008 after the satellite had drifted to a lower orbit for roughly two years.

[2]See http://dels.nas.edu/basc/trmm for presentations from the workshop.

FINDINGS

NASA and JAXA are to be commended on the highly successful TRMM satellite whose achievements and longevity have exceeded even the optimistic expectations at the time of launch. These agencies are also to be commended for their visionary actions to extend the lifetime of TRMM beyond the original anticipated maximum length of the mission thereby enhancing the value of the data from TRMM to science and operations. The committee found the following:

- TRMM has two unique attributes that make it ideal for observing tropical rainfall systems: (1) its suite of complementary observing instruments, and (2) its orbital characteristics.

    1. The Precipitation Radar (PR) is the only precipitation radar in space and provides direct, fine-scale observations of the three-dimensional structure of precipitation systems. The combination of PR and Lightning Imaging Sensor (LIS) observations provides a measure of convective intensity.[3] The combination of PR, TRMM Microwave Imager (TMI), and Visible and Infrared Scanner observations from the same platform serves, in effect, as a "Rosetta Stone" for cross-calibration of the indirect estimates of precipitation from microwave, visible, and infrared observations.
    2. The TRMM orbit (low altitude, non-sunsynchronous, precessing, 35-degree tropical inclination) provides sampling in the tropics that is far more frequent, and far more spatially comprehensive than that obtained from standard polar orbiter satellites.

- TRMM has achieved its original science goals and produced a greater than expected range of scientific results in

    1. climate and weather research (e.g., a reliable seven-year climatology of the mean annual tropical rainfall and its interannual and diurnal cycles; fundamental new information on the synoptic climatology of tropical weather systems, e.g., the first detailed precipitation and latent heating profiles throughout the tropics and subtropics, first detailed convective and stratiform rainfall structure, and a description from space of the fine-scale structure of rainfall systems that can only be determined from the PR data; understanding of how sea surface temperature patterns modify precipitation through air-sea interaction; quantitative documentation of precipitation patterns; mapping sea surface temperature through clouds for improved climate

[3]The TRMM Microwave Imager also can gauge convective intensity, but the PR and LIS data are principally used.

records; demonstrating the effect of pollution and other human influences on precipitation formation); and

2. applied research (e.g., a wealth of climatological and diagnostic information on tropical rainfall; insight on the physical processes of precipitation formation; unique, fine-scale information on hurricane and typhoon structure linked to rapid intensification; calibration of a long-term satellite precipitation dataset and multisatellite three-hour analyses; experimental tropical cyclone forecast methods; enhanced sea surface temperature nowcasting applications using TMI data; integration of TRMM data into forecast model initialization procedures; enhanced understanding of tropical cyclone inner eyewall dynamics and tropical cyclone intensity).

• Since 1998, TRMM has provided near-real-time information for operational purposes. Data from the TMI sensor are most often used. There are four principal applications: (1) monitoring and predicting the future behavior of tropical cyclones, (2) estimating rainfall, (3) predicting weather, and (4) monitoring of climate variability (precipitation and sea surface temperature). Many organizations and individuals have invested in bringing TRMM data into the operational environment because of the unique aspects of TRMM's orbit and sensor suite. This reflects their professional judgment of the value of doing so based on their experiences of improvements in such things as accuracy of center fixes for tropical cyclones and prediction of storm intensity. Nonetheless, the effect of TRMM data on operational applications has not been widely quantified because the data record is too short for meaningful statistical analysis and no one has done control experiments wherein the TRMM data are eliminated and the analysis is rerun. Further, the socioeconomic effects on end-users of improved forecasts have not been quantified.

In the United States TRMM data are used in operations by NOAA organizations (e.g., Tropical Prediction Center, National Centers for Environmental Prediction, Satellite Analysis Branch, Aviation Weather Center, Climate Prediction Center, National Climate Data Center) and the Department of Defense (e.g., Joint Typhoon Warning Center, Air Force Weather Agency, Fleet Numerical Meteorology and Oceanography Center, Naval Research Laboratory). TRMM data are used internationally for operations by World Meteorological Organization centers throughout the tropics for monitoring and forecasting tropical cyclone activity. Groups in Japan and Europe have begun using TRMM data in numerical weather prediction models. Because TRMM data are already being used operationally (which does not fit with NASA's primary focus of research and exploration) NASA has sought partnerships with other agencies to fund extension of TRMM. Thus, determining the future of TRMM has become a multi-agency issue.

• TRMM's potential to help improve forecasts—especially through increased use of PR data in models—has not been fully realized because of

1. the PR data having only recently become available in near real time to the broader community outside of NASA and JAXA,
2. the new and unique nature of the PR data and the learning required to exploit them,
3. the perceived experimental nature and finite lifetime of the PR, and
4. the lack of sophistication in the representation of cloud and precipitation physics in current operational forecast models and global climate models such that they cannot yet take advantage of the native resolution of the PR data.

- The TRMM satellite and its sensors remain in excellent condition. There is every reason to believe that they will continue to operate well for the next few years.
- NASA will incur costs for operating the TRMM satellite through 2007 even if the mission is terminated in December 2004, because of the time it takes for the spacecraft to drift down to an appropriate altitude for controlled reentry. These costs exceed the amount currently in NASA's budget for TRMM. The additional cost of extending TRMM from December 2004 to November 2005 is approximately $4 million. It is NASA's practiced policy to try to recover its costs of mission extension from related research programs. In the case of TRMM, these extra costs would likely have to be borne by NASA's precipitation research budget, which is around $16 million per year. However, it is outside this committee's charge to assess the effects on other satellite operations, missions, and research budgets of NASA bearing the entire cost of extending TRMM, though such an assessment is part of the overall decision context.
- The most recent analyses of the risks from uncontrolled reentry are those reported in 2001 (Pielke et al., 2001) and 2002 (Martin, 2002) (see Chapter 2), and the committee is unaware of any subsequent changes to the conclusions. Although the risk from uncontrolled reentry is part of the overall decision context, the committee is neither tasked to assess this risk nor does it have the expertise to do so.

CONCLUSIONS

- The material in this National Research Council report provides science and operations information needed as input for a qualitative evaluation of the balance between the risk inherent with an uncontrolled reentry and the contribution through operations and research to the protection of life and property of an extension of the TRMM mission. Extension of the mission to at least late 2005 will provide time for further examination of the relevant issues.
- There are persuasive reasons to believe that significant contributions of TRMM to operations and science will continue if the mission is extended. The committee's conclusions about operational and research benefits of extending

TRMM to the fuel point in approximately December 2005 and beyond are compiled in Table ES-1.

• From the perspective of anticipated research contributions, TRMM is worth continuing for six primary reasons.

1. TRMM provides a unique complement of measurements. Specifically, the PR, the passive microwave imager, and the visible and infrared instruments provide a powerful overlap of precipitation, cloud, and water vapor measurements and the LIS helps isolate intense convective cells. The TMI permits sea surface temperature measurement through clouds at high spatial resolution. Continuation of the mission is vital to the future development of spaceborne PR technology, especially in the evaluation of radar technology life cycle.
2. Mission extension creates the opportunity for cross-calibration, validation, and synergy with sensors on future missions, such as CloudSat and the A-Train satellite series, the National Polar-orbiting Operational Satellite System's Conical Scanning Microwave Imager/Sounder, and the Global Precipitation Measurement core satellite and other constellation satellites.
3. TRMM's unique low-inclination, low-altitude, precessing orbit enhances science by providing unique spatial and temporal information that fills gaps in data from other current and upcoming polar-orbiting satellite sensors.

TABLE ES-1 Anticipated Operational and Research Contributions due to Extending TRMM to the Fuel Point (approximately December 2005) and Beyond

Anticipated Contributions of TRMM Up to the Fuel Point (when controlled reentry is still possible)	Additional Anticipated Contributions of TRMM Beyond the Fuel Point (i.e., in addition to what is gained up to the fuel point)
OPERATIONS	OPERATIONS
• Another year of TMI and PR data for tropical storm monitoring and forecasting**	• Technology demonstration of the endurance of the first precipitation radar inspace*
• Another year of TMI data for numerical weather prediction**	• Improved forecasts from the operational assimilation of PR and TMI data into weather and climate prediction models**
• Another year of PR and TMI data for enhancing near-real-time rainfall products**	
• Another year of lightning data for air traffic advisories*	
• Realizing the potential to use PR as a global rainfall reference standard*	

TABLE ES-1 Continued

Anticipated Contributions of TRMM Up to the Fuel Point (when controlled reentry is still possible)	Additional Anticipated Contributions of TRMM Beyond the Fuel Point (i.e., in addition to what is gained up to the fuel point)
RESEARCH • Overlap with CloudSat radar operations and the A-Train satellite series** • Overlap with the Coriolis WindSat sensor** • Unique opportunities to enhance field experiments (TCSP, TEXMEX-II)** • Unique opportunities to enhance international research programs (GEWEX, THORPEX, Hurricane Field Program)** • TRMM's Precipitation Radar provides a calibration reference for the current GPM mission-like constellation of microwave satellite sensors** • TRMM is a catalyst for tropical cyclone research (e.g., research on convective bursts, tropical cyclone eyewall replacement cycles, improved forecasting of inland flooding during hurricanes)** • Longer TRMM record needed for tropical cyclone forecasting* • Longer TRMM record needed for climate research* • Foster improving moist physics parameterization for climate models, numerical weather prediction, and related assimilation systems by evaluating models of clouds and precipitation physics*	RESEARCH • Unique opportunities to enhance field experiment (AMMA)** • Developing the next generation hurricane forecast model** • Seamless transition into the Global Precipitation Measurement (GPM) mission* • Realization of a prototype GPM-like operation* • Avoiding researchers being ill-prepared for GPM** • Better characterization of interannual variability and the El Niño-Southern Oscillation cycle*

NOTE: See Appendix J for acronym definitions for field experiments and programs. We use a single asterisk to differentiate applications that use TRMM data only, or as the primary component of a research or operational activity, from those that use TRMM data as a complementary component of an operational or research activity (marked with a double asterisk). There is a gray area between these two categories, but the distinction serves as a first-order attempt to differentiate between essentially stand-alone contributions and complementary but still unique contributions of TRMM.

4. TRMM data will enhance field experiments and programs (e.g., TCSP, AMMA, GEWEX, THORPEX, TEXMEX-II [see Appendix J for explanations of program name abbreviations]), tropical cyclone research—including tropical cyclone forecasting—and development of cloud-resolving models.

5. A longer record is required to collect enough examples to cover the parameter space of synoptic variability more fully. For example, over the first six years of TRMM data, the TMI instrument passes within 750 km of storm centers during one of every eight orbits, whereas PR observes within 250 km of the center during one of every 25 orbits. The narrow swath of the PR and the rare occurrence and great variability of tropical cyclone structure, intensity, and precipitation amount strongly argues for mission extension to increase sample sizes for statistical analyses.

6. Longer TRMM data records will better characterize tropical seasonal-interannual climate variability in general and the El Niño-Southern Oscillation (ENSO) cycle in particular. ENSO is the dominant mode of global interannual climate variability. TRMM provides quantitative ENSO-related tropical rainfall anomalies that are needed to improve our understanding of both the local and remote effects of this phenomenon, and ultimately to make better predictions of its socioeconomic effects in both the tropics and extratropics.

• TRMM's reliability combined with the value of TRMM data to operations shows the satellite's potential as an operational system. From a perspective of anticipated operations contributions TRMM is worth continuing for three primary reasons.

1. TRMM data from the TMI and PR sensors have a demonstrated capability (for TMI) or potential capability (for PR) to improve the weather forecasting process, especially for monitoring and forecasting the tracks and intensity of tropical cyclones and the intensity of rainfall they yield.

2. Continuation of the TMI data stream would enable modelers and forecasters to continue to improve the overall numerical weather prediction process (i.e., model development and validation, forecast initialization, and forecast verification). This includes use of TMI in calibrating similar data from other microwave sensors and contributes to improved global as well as tropical precipitation monitoring and prediction.

3. PR data are an underexploited yet unique resource. Having them available in near real time for an extensive period of time would foster investment of time and effort to make full use of PR data in the forecasting process.

• Considering the past and expected scientific and operational contributions presented in this report, important benefits would be obtained if TRMM were extended until it runs out of fuel. Although the scientific and operational arguments by themselves point toward maximum extension of the TRMM satellite life, the committee is concerned that there has not been proper consideration of all three elements of the decision (benefits, costs, and risk). The committee recognizes that consideration of the associated costs and reentry risks has to be part of the decision equation, which requires a solution acceptable to both the user and interagency communities.

RECOMMENDATION

The committee strongly recommends continued operation of TRMM, at least until such time as a decision on controlled reentry becomes unavoidable. The additional year can be used to more fully weigh the benefits, costs, and risks.

1

Introduction

SCOPE OF THE REPORT

This is the interim report of the Committee on the Future of the Tropical Rainfall Measuring Mission (TRMM) (see Appendix A). The charge to the committee in this first phase of its work is to conduct a workshop and prepare an interim report to be delivered in December 2004 on how best to use the remaining TRMM spacecraft life. In particular, the committee and workshop participants were asked to consider:

- scientific and research contributions of TRMM to date and those expected if TRMM is continued;
- operational contributions of TRMM to date and those expected if TRMM is continued;
- assessment of expected benefits of continuing TRMM operation until (1) fuel is depleted to the level needed for a controlled reentry (around December 2005) and (2) all fuel is depleted (estimated to be 2010-2011).

A later phase of the committee's work will focus on needs for satellite-based measurements of tropical rainfall beyond TRMM (see Appendix B).

The decision context for mission extension has three major components: the operational and research benefits of extension, financial constraints, and risk to life and property during satellite reentry. In December 2004 the National Aeronatuics and Space Administration (NASA) will weigh the research and operational benefits against the cost of extending the mission for approximately one year. If NASA decides to continue TRMM, a second decision point will be forced in approximately December 2005. At that point the agency will have to weigh the societal benefits of TRMM against both the additional cost and the risk of an uncontrolled reentry if the remaining fuel is used to maintain the satellite's orbit rather than to guide the spacecraft into the ocean.

The committee's task focused on the research and operational benefits component of the decision. The committee was not tasked to analyze the risk or cost components, although these components are part of the overall context and thus laid out in Chapter 2. Chapter 3 describes the achievements of TRMM in research and operations to date and Chapter 4 looks to the potential future research and operational applications of TRMM. Chapter 4 differentiates between the potential contributions from a TRMM extension until fuel is depleted to a level that is still sufficient for a controlled reentry or until all fuel is depleted. A series of appendixes provides supporting information that is referenced in the body of the report.

AUDIENCE FOR THE REPORT

The audience for this report includes NASA and the Japan Aerospace Exploration Agency (JAXA), operational agencies (e.g., the National Oceanic and Atmospheric Administration [NOAA], Department of Defense agencies), Congress (e.g., House Science Committee), the White House Office of Science and Technology Policy and Office of Management and Budget, the scientific community in general, and users in particular.

INFORMATION GATHERING AND WORKSHOP DIMENSIONS

The committee gathered information using four approaches.

1. inviting presentations at a workshop on November 8, 2004 (see Appendix C);
2. promoting and tracking discussion at the workshop (from participants in the room and on the phone [see Appendix D]);
3. reviewing existing written materials, such as peer-reviewed papers, reports, information from Websites, and letters; and
4. soliciting input to a Website that posed questions relating to the committee's phase I task.

The workshop had four sessions (Appendix C) with formal input from 14 people. Approximately 45 people attended the workshop and participated in general discussion. Participants from Japan attended on an open phone line. The formal presentations are available on the Web.[1]

[1] See http://dels.nas.edu/basc/trmm.

HISTORY OF THE TROPICAL RAINFALL MEASURING MISSION

The TRMM was motivated by recognition of the fundamental importance of precipitation in Earth's climate system, the inadequate network of surface precipitation measurements over much of Earth, and recognition of the crucial role of tropical rainfall in global climate dynamics and the global hydrologic cycle.

The TRMM science plan was developed in the late 1980s (Simpson et al., 1988). The overarching mission science goal was to advance knowledge of global water and energy cycles by observing from space the temporal and spatial distribution of tropical rainfall and associated latent heating. TRMM thus carried a suite of five sensors (Box 1-1 and Figure 1-1) designed to address seven key science questions (Box 1-2).

TRMM was launched in November 1997 as a joint effort of NASA and JAXA. It has a low-inclination, precessing orbit between 35°north and 35°south. The mission was designed as a science path-finding experiment that would last a minimum of three years with an initial goal of five years. Based on TRMM's excellent performance and promise, NASA and JAXA decided in 2001 to extend the mission. TRMM's orbit was boosted from 350 km to 402.5 km to reduce drag and conserve fuel.

TRMM has now been operating successfully for seven years. Initially the TRMM data were provided to users in a delayed mode because of the mission's original focus on research. Since the data became available in near real time in Fall 1998, they have been increasingly used in operational applications, especially for monitoring and predicting tropical cyclones.

As a consequence of TRMM's success the research and operational communities have created a demand for the continuation of TRMM data (see, for example, Appendixes E through H). To date, however, no party outside NASA has stepped forward to contribute to the cost of continued TRMM operations. Although NASA and JAXA agreed to decommission TRMM in July 2004, TRMM is being kept alive through 2004 because of pressure from the research and operational community that ultimately led to a direct request from the NOAA administrator to the NASA administrator (Appendix H and I).

GLOBAL PRECIPITATION MEASUREMENT MISSION

Since 2001, NASA, JAXA, and other international partners have been planning the Global Precipitation Measurement (GPM) mission, a follow-up on TRMM to measure precipitation on a global scale (NASA, 2004). GPM is envisioned as a constellation of approximately eight satellites, with a core satellite similar to TRMM. All of these satellites will carry passive microwave sensors for rainfall estimation. Key sensors onboard the core spacecraft will be a dual-frequency precipitation radar and a multichannel microwave imager. GPM goes beyond TRMM in several important ways: The number of satellites in the con-

BOX 1-1
Instruments Onboard TRMM

The TRMM observational system described in the 1988 science plan (Simpson, 1988) consisted of three instruments: a Precipitation Radar (PR), a Microwave Imager (TMI), and a Visible and Infrared Scanner (VIRS). Two additional sensors were added before the November 1997 launch: a Lightning Imaging Sensor (LIS) and a Clouds and Earth Radiant Energy System (CERES) instrument.

- PR is the key TRMM instrument. It was the first and continues to be the only spaceborne weather radar. It provides three-dimensional profiles of storm structure as well as intensity and vertical and horizontal distribution of precipitation and precipitation type.
- TMI is a multichannel, dual-polarized, conically scanning passive microwave instrument designed to provide quantitative estimates of rainfall, water vapor, cloud water content, and sea surface temperature by measuring the minute amounts of microwave energy emitted from Earth and its atmosphere.
- VIRS provides a very indirect observation of rainfall. It senses radiation emitted from Earth in five spectral regions ranging from visible to infrared.
- LIS detects lightning, even in the presence of bright clouds. This sensor can “stare” at the same point for up to 80 seconds, enabling it to determine lightning rates.
- CERES measured the energy levels at the top of the atmosphere and could provide estimated energy levels within the atmosphere and at Earth’s surface. This instrument failed about eight months after launch.

The combination of instruments onboard TRMM provides a unique resource for cross-calibration with other remotely sensed precipitation estimates. The TRMM satellite radar and radiometer combination—PR, TMI, and VIRS—was designed to obtain high-quality vertical precipitation profiles as well as surface rainfall estimates. TRMM’s rainfall-rate observations from the combined radar and passive microwave instruments—PR and TMI—calibrate the empirical rain estimates from the visible and infrared radiometer. VIRS therefore allows comparison with and calibration of the National Polar-Orbiting Operational Environmental Satellite System and Geostationary Operational Environmental Satellites.

Kummerow et al. (2000) provide more detail on the TRMM instruments, algorithms, and a wide range of early results.

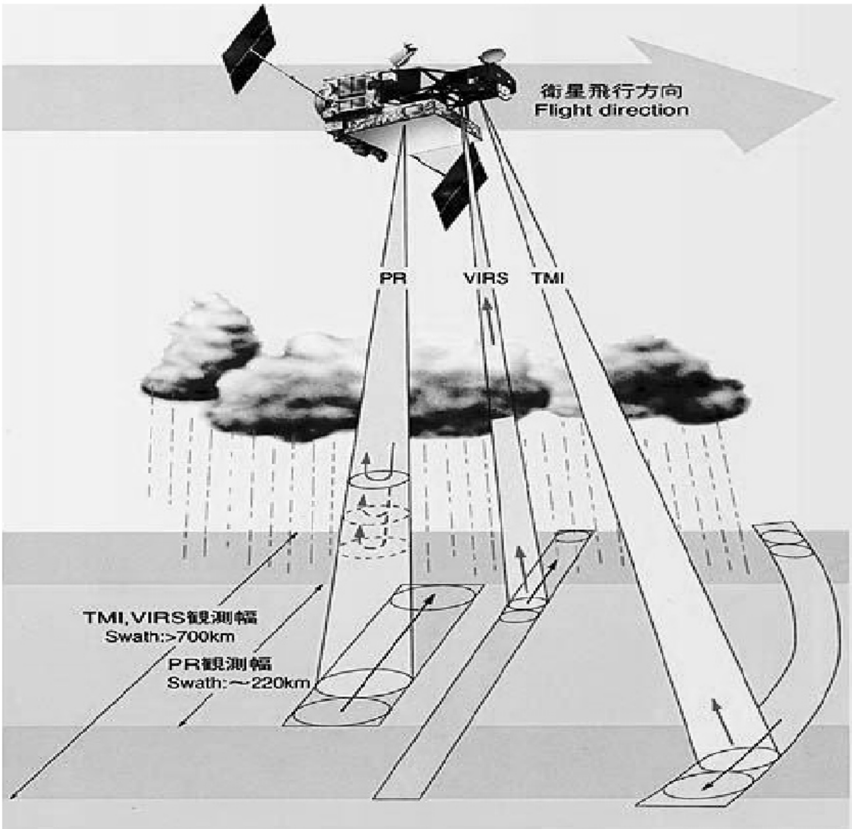

FIGURE 1-1 Schematic illustration of the TRMM satellite sensors and how they collect data. SOURCE: Presentation by Jack Kaye, NASA, at November 8, 2004, workshop.

stellation will facilitate a significant reduction in revisiting time (a three-hour sampling interval is anticipated) over TRMM, the core satellite will cover a broader latitudinal band (up to approximately 50 degrees), and the dual-frequency precipitation radar will assist in reducing uncertainty due to raindrop size variability and also measure lighter precipitation than TRMM. The GPM launch is currently projected for 2010 at the earliest.[2]

[2]As stated by Mary Cleave, NASA, at the committee's November 8, 2004, workshop. For up-to-date GPM information, visit the mission Website at http://gpm.gsfc.nasa.gov.

BOX 1-2
The Original Seven Priority Science Questions to be Addressed by TRMM

1. What is the four-dimensional structure of latent heating in the tropical atmosphere? How does it vary diurnally, intraseasonally, seasonally, and annually?
2. What is the role of latent heat released in the tropics in both tropical and extratropical circulation?
3. What is the monthly average rainfall over tropical ocean areas of about 10^5 km^2 and how does this rain and its variability affect the structure and circulation of the tropical oceans?
4. What is the relationship between precipitation and changes in boundary conditions at Earth's surface (e.g., sea surface temperature, soil properties, vegetation)?
5. What is the diurnal cycle of tropical rainfall and how does it vary in space?
6. What are the relative contributions of convective and stratiform precipitation and how does it vary in space?
7. How can improved documentation of rainfall improve understanding of the hydrological cycle in the tropics?

2

Decision Context

INTRODUCTION

The Tropical Rainfall Measuring Mission (TRMM) case exemplifies a broader challenge faced by the National Aeronautics and Space Administration (NASA) and other federal agencies that operate research satellites and sensors that work superbly past completion of their primary scientific mission and hold impressive possibilities for both scientific and operational advances.[1] Extending TRMM is also part of the larger question of how the United States manages the transition from research to operations, and from one agency to others. Earlier reports (e.g., NRC, 2003) have tackled aspects of this issue and the subsequent phase of this committee's work will step back and examine the broader challenges of research to operations in the context of precipitation missions. This chapter covers the elements of the TRMM decision in this broader context.

ELEMENTS OF THE TRMM DECISION CONTEXT

There are three elements to be weighed in the TRMM decision context:

1. Research and Operations Benefits
2. Cost
3. Risk

[1]The United States and other countries pursue such advances in order to improve short- and long-term forecasts in the belief that such forecasts provide socioeconomic benefits to the population.

Chapter 4 of this report highlights the research and operational benefits of mission extension. Cost refers to the cost of mission operations, controlled reentry, and science data processing. Risk refers to the risk to lives and property from spacecraft debris in the event of uncontrolled reentry.

COST

The mission cost of TRMM to date is at least $750 million.[2] Even if NASA terminates TRMM in December 2004, there will be more than $13 million in additional costs for operating the satellite until 2007 when controlled reentry would occur.[3] There is no question that NASA and the Japan Aerospace Exploration Agency have invested large sums in TRMM beyond the spacecraft's original planned five-year life and they should be commended for this.

The cost of mission extension beyond 2004 is illustrated in Table 2-1. These calculations are for extension of operations to November 2005 and controlled reentry in the first quarter of 2008 after roughly two years of driftdown. NASA has approached other agencies for their help in supporting the cost of extending the mission beyond 2004 but without success to date.[4] Current NASA policy regarding mission extensions puts the burden on research programs to underwrite costs incurred by NASA.[5] The current NASA precipitation research budget is around $16 million per year.

The key budget number in Table 2-1 is the combined cost of mission operations and controlled reentry in fiscal year 2005, that is, $4.3 million. This is the approximate additional cost of operating TRMM until November 2005 instead of December 2004.[6] NASA separates the total cost into three components: mission operations, controlled reentry, and science data processing. The first and last of these are approximately equal and collectively contribute 90 percent or more to the overall annual cost in Table 2-1. Science data processing includes TRMM-related, Global Precipitation Measurement (GPM)-related, and general precipitation data processing costs and is not uniquely tied to the TRMM mis-

[2]Lawler (2004) quotes a figure of $600 million. According to Robert Adler, NASA, this is probably an approximate cost of building and launching TRMM. By considering cost of data processing for 10 years and science team support for 7 years, the estimated cost increases to approximately $750 million. This is still a minimum estimate, since the full cost from the Japanese contribution to TRMM is not included.

[3]Costs are drawn from data presented to the committee by Jack Kaye, NASA. There is roughly a two-year window after termination when the satellite drifts to a lower orbit in preparation for reentry.

[4]Jack Kaye, NASA, indicated this in his presentation to the committee at the November 8 workshop.

[5]Ibid. Mary Cleave, NASA, confirmed this policy at the November 8 workshop.

[6]This estimate is in addition to the roughly $13 million (mentioned above) that would be incurred during the three fiscal years after termination while the spacecraft drifted down in preparation for controlled reentry.

TABLE 2-1 Cost Breakdown (in millions of dollars) for Extending TRMM Mission to November 2005 (official end of the 2005 hurricane season) with Controlled Reentry in the First Quarter of Fiscal Year (FY) 2008

	FY04	FY05	FY06	FY07	FY08	Total
Mission Operations[a]	6.4	3.8	3.6	4.0	2.5	20.3
Controlled Reentry[b]	1.0	0.5	0.5	0.6	0.5	3.1
Science Data Processing[c]	4.8	3.6	3.4	3.5	1.8	17.1
Total	12.2	7.9	7.5	8.1	4.8	40.5
Guideline[d]	12.2	4.7	4.7	4.9	1.5	28.0
Shortfall[e]	0.0	–3.2	–2.8	–3.2	–3.3	–12.5

NOTE: There are two caveats to this table. First, operating costs are projected to be lower than current values in fiscal year 2005 and beyond because of current efforts to increase automation within flight operations, thereby reducing staffing levels. No reserves are included in the estimates to mitigate the risks of not achieving these reductions or from risks due to other factors (e.g., NASA's Goddard Space Flight Center manpower and other annual rate fluctuations). Second, the estimates reflect the "most probable" timing for reaching controlled reentry fuel threshold of 138 kg and a fiscal year 2004 Program Operating Plan guideline.

[a]Cost of maintaining staffing of flight control.
[b]Cost of analysis, training, and staffing for reentry maneuvers.
[c]Cost of (1) reprocessing existing data, (2) transition to a new precipitation processing system for GPM, and (3) development of multisatellite three-hour precipitation products (these three items are not always clearly separable).
[d]Funds in NASA Goddard's May 2004 budget to cover TRMM operations.
[e]Difference between estimated total cost and funds in the NASA Goddard budget for this activity.

SOURCE: Steven Neeck, NASA.

sion or its extension.[7] For example, the budget line covers the cost of (1) reprocessing existing TRMM datasets for improved rainfall algorithms, (2) the transition to a new precipitation processing system that is part of GPM preparations, and (3) the development of multisatellite three-hour precipitation products that will be produced regardless of the availability of new TRMM data. The distinction between these functions is not always exact, which makes it difficult to give a precise figure for the portion of the data processing budget that is directly

[7]Indeed, with the planned GPM mission, these activities will likely continue for many years.

attributable to TRMM extension. The drop of the data processing budget line in fiscal year 2008 reflects winding down of the TRMM Scientific Data and Information System, which will be replaced by the GPM system as that mission prepares for launch. Overall, the actual cost of a mission extension is dominated by the mission operations budget line. And the shortfall line in Table 2-1 indicates that a significant fraction of that cost is not covered in the current NASA Goddard budget.

RISK

The TRMM spacecraft has sufficient mass to prevent it from entirely burning up when it reenters Earth's atmosphere. To date, the spacecraft's propulsion system has been used to maintain the craft's orbit. Orbital adjustments every few weeks use some of the fuel on board. The propulsion system can also be used to conduct a controlled reentry whereby the satellite is guided into the ocean. NASA estimates that a controlled reentry of the satellite requires 138 kg of fuel. At the current rate of fuel usage the fuel would be depleted to 138 kg in late 2005 to early 2006 (Figure 2-1).[8] If all the remaining fuel were to be used for orbit adjustments, NASA estimates that TRMM could continue operating until 2010 or 2011 and then drift down for an uncontrolled reentry.

NASA is responsible for a handful of uncontrolled reentries each year. For example, in 1999, 111 large objects reentered Earth's atmosphere in an uncontrolled way. 21 of the objects were satellites and the remainder was primarily rocket bodies used to boost satellites and platforms. 29 of the 111 objects originated from the United States and NASA was responsible for 6 of these 29 objects (Martin, 2002).

NASA guidelines state that an orbital reentry risk level of 1 in 10,000 is acceptable.[9] Other U.S. government agencies have also accepted this risk level as a standard guideline (Martin, 2002). In a 2002 TRMM Disposal Risk Review (Martin, 2002), NASA's Office of Safety and Mission Assurance estimates that there is a 2 in 10,000 casualty risk associated with an uncontrolled reentry of TRMM. The review states that the TRMM uncontrolled reentry casualty risk is in an "intermediate, or tolerability zone, where the risk may be tolerated in return for other (public safety) benefits" (Box 2-1). The broader context of benefits and risks associated with TRMM extension was discussed at a 2001 NASA-supported workshop (Box 2-2). The basic conclusions of the 2001 workshop remain current.[10]

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[8]Robert Adler, NASA, at the November 8 workshop.

[9]See NASA Policy Directive 8710.3B *NASA Policy for Limiting Orbital Debris Generation* and NASA Safety Standard 1740.14 *Guidelines and Assessment Procedures for Limiting Orbital Debris* referenced by Jack Kaye, NASA, at the November 8 workshop.

[10]As argued by Roger Pielke, Jr., in his presentation at the November 8 workshop.

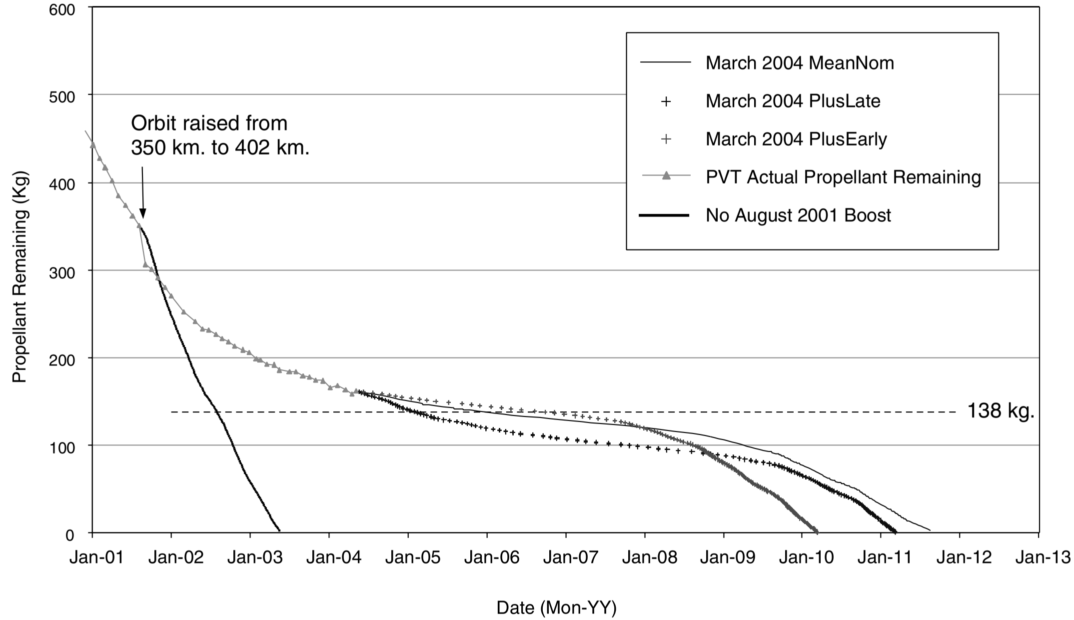

FIGURE 2-1 Fuel ("propellant") levels aboard the TRMM satellite and projected rate of decrease (March 2004 projections). The horizontal line marked "138 kg" indicates the critical fuel level below which reentry cannot be controlled. When the fuel level reaches zero, the ability to make orbital adjustments is lost, the TRMM data stream degrades, and driftdown begins. The extension of the lifetime of TRMM due to the orbital boost in 2001 is evident from the difference between the original projected zero fuel point in 2003 and the various options in 2010-2011. The three curves that intercept the horizontal axis in 2010-2011 are for three different solar flux forecast scenarios: (1) mean expected flux and nominal phase of the solar cycle (the line with the latest intercept on the X-axis); (2) sigma plus flux and late phase (the line intercepting near January 2011); and (3) 2 sigma plus flux and early phase (the line intercepting near January 2010). The mean nominal curve is considered the most likely fuel expenditure scenario. SOURCE: Presentation by Robert Adler, NASA, at November 8 workshop.

BOX 2-1
Conclusions from 2002 TRMM Disposal Risk Review by NASA Office of Safety and Mission Assurance (Martin, 2002)

"In the case of a TRMM uncontrolled reentry, the casualty risk of 2/10,000 events appears to fall into an intermediate, or tolerability zone, where the risk may be tolerated in return for other (public safety) benefits.

A (defendable) quantitative estimate of the benefits derived from up to five extra years of TRMM data on improvement of storm analysis, forecasting, and public safety could not be developed. As a result NASA will need to rely on subjective estimates based on expert judgment.

There are other factors that decision makers should consider in making an informed decision including: possible legal considerations, policy considerations, and international considerations.

Barring any impediments from NASA Legal Council, it is concluded that a decision to accept the uncontrolled reentry public safety risk of TRMM, in exchange for extending the mission and potentially benefiting from the improvement in storm analysis and forecasting capabilities, is reasonable and within the discretion of the Earth Science Enterprise and the NASA Administrator.

Note: If the decision is made to extend the TRMM mission, consideration should be given to maintaining the controlled reentry capability as long as possible in case the critical TRMM instruments fail or a replacement capability becomes operational prior to fuel levels reaching the critical 156 kg level."

FINDINGS

FINDING 2.1:[11] NASA will incur costs for operating the TRMM satellite through 2007 even if the mission is terminated in December 2004, because of the time it takes for the spacecraft to drift down to an appropriate altitude for controlled reentry. These costs exceed the amount currently in NASA's budget for TRMM. The additional cost of extending TRMM from December 2004 to November 2005 is approximately $4 million. It is NASA's practiced policy to try to recover its costs of mission extension from related research programs. In the case of TRMM, these extra costs would likely have to be borne by NASA's precipitation research budget, which is around $16 million per year. However, it is outside this committee's charge to assess the effects on other satellite operations, missions, and research budgets of NASA bearing the entire cost of extending TRMM, though such an assessment is part of the overall decision context.

FINDING 2.2: The most recent analyses of the risks from uncontrolled reentry are those reported in 2001 (Pielke et al., 2001) and 2002 (Martin, 2002), and the committee is unaware of any subsequent changes to the conclusions. Although the risk from uncontrolled reentry is part of the overall decision context, the committee is neither tasked to assess this risk nor does it have the expertise to do so.

[11]All of the committee's findings appear in the Executive Summary, though not in the order they appear in the report.

BOX 2-2
Outcomes of 2001 NASA Workshop on Risk-Benefit Assessment of Observing System Decision Alternatives

The workshop was held at the University Corporation for Atmospheric Research in Boulder, Colorado in June 2001. The four workshop goals are quoted below, along with the related findings and recommendations.

- **Workshop Goal 1:** Estimate the benefits associated with TRMM data in the context of operational forecasting (particularly associated with tropical cyclones), and the associated loss of benefits in the absence of TRMM data. Such estimates will include consideration of uncertainty.

    - o *Finding 1.1: All workshop participants agreed that the TRMM data are now being, and will continue through the remaining lifetime of the mission to be, used by agencies in the United States and abroad to aid operational marine forecasting, especially in the data-sparse Pacific and Indian oceans.*
    - o *Finding 1.2: Participants agreed unanimously that the risk to human life of not having TRMM data available for operational uses cannot presently be accurately quantified.*
    - o *Finding 1.3: Most, but not all, workshop participants subjectively estimated that the risk to human life of an uncontrolled reentry would be exceeded by the risk to human life of not having TRMM data for operational uses.*

Recommendation 1.1: If NASA wishes to use risk assessments as a basis for deorbiting assessments, the agency must consider such risks and benefits more comprehensively than it presently does.

Recommendation 1.2: Given the material presented at the workshop, we recommend that NASA should not base its decision to extend the TRMM mission primarily on quantitative comparisons between "lives potentially saved" through operational exploitation of TRMM data and "potential hazard" associated with uncontrolled reentry.

- **Workshop Goal #2:** Place the risk and benefit information into the context of the various decision alternatives that NASA is faced with for the future of the TRMM satellite.

    - o *Finding 2.1: The present and projected health and performance of TRMM are excellent in the context of experience with research satellites.*
    - o *Finding 2.2: Workshop participants unanimously endorse boosting the TRMM orbit as soon as possible from 350 km to 400 km, so long as the scientific community also endorses this alternative.*

Recommendation 2.1: During the approximately 3 years of additional on-orbit operations that would be provided by boosting TRMM, NASA should (a) reevaluate its deorbiting decision guidelines, (b) conduct that research necessary to more comprehensively and better understand risks and benefits associated with deorbiting decision alternatives, and (c) with the reevaluated decision criteria and results of research related to risks and benefits, revisit the TRMM deorbiting decision in late 2004.

continued

BOX 2-2 (continued)

- **Workshop Goal #3:** Review engineering studies of risks associated with alternative TRMM reentry strategies, including consideration of the accuracy and estimates of the uncertainty associated with such studies.

  - o *Finding 3.1: As presented at the workshop, uncertainties in potential risks of uncontrolled reentry are so large as to diminish substantially the usefulness of this calculation as a decision threshold.*

Recommendation 3.1: NASA should consider (a) making its reentry risk calculation more transparent, rigorous, and meaningful and (b) placing its reentry risk calculations into a more comprehensive framework.

- **Workshop Goal #4:** Consider a longer-term strategy for "technology assessment of observing systems" to provide decision makers with reliable and scientifically robust knowledge of risks and benefits associated with similar future situations.

  - o *Finding 4.1: To primarily, or even jointly, serve direct operational functions, the TRMM program would likely be designed, managed, and implemented in a very different manner than it has been as a research program.*
  - o *Finding 4.2: If advances in engineering design and launch vehicle success rates allow for the potential extension of research missions beyond original plans, then this creates a new set of decisions for the remote sensing science community.*
  - o *Finding 4.3: Decision makers lack knowledge necessary to prioritize observational programs and plans according to their contributions to science and society.*

Recommendation 4.1: Decision makers would benefit from an ongoing effort devoted to the "technology assessment of observing systems" that would seek to evaluate the broad costs and benefits of alternative observing strategies for both science and society.

Recommendation 4.2: NASA and its operational partners would benefit from a more systematic approach to the "transition of research to operations."

The full workshop report can be viewed at http://sciencepolicy.colorado.edu/pielke/workshops/trmm/index.html.

3

Achievements of TRMM to Date

INTRODUCTION

The National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) developed the Tropical Rainfall Measuring Mission (TRMM) primarily to demonstrate the utility of space-based radar and passive microwave sensors for measuring precipitation and associated hydrological processes. This aspect of TRMM has succeeded beyond expectation. Other than the Clouds and Earth Radiant Energy System (CERES) instrument, which failed eight months after launch of the satellite, the systems have operated flawlessly for seven years, during which time they have produced large amounts of research-quality data and value-added real-time operational support. As a result, uncertainty in space-based measurement of tropical rainfall has been greatly reduced from earlier estimates.

As this chapter will demonstrate, the science priority questions in the original TRMM science plan (see Box 1-2) have largely been addressed. The insights gained from TRMM so far and the wealth of information that continues to be provided by TRMM has enabled the science community to further advance its objectives in trying to understand the nature of tropical hydrometeorology and climate. Perhaps the success of this mission is best reflected in the decision to pursue the follow-on Global Precipitation Measurement (GPM) initiative.

This chapter summarizes the effect of TRMM on science and operations, highlights the many unique attributes of TRMM that make the mission valuable to science and operations, examines the longevity and current state of its instruments, and presents a broad summary of the research and operational achievements of TRMM to date.

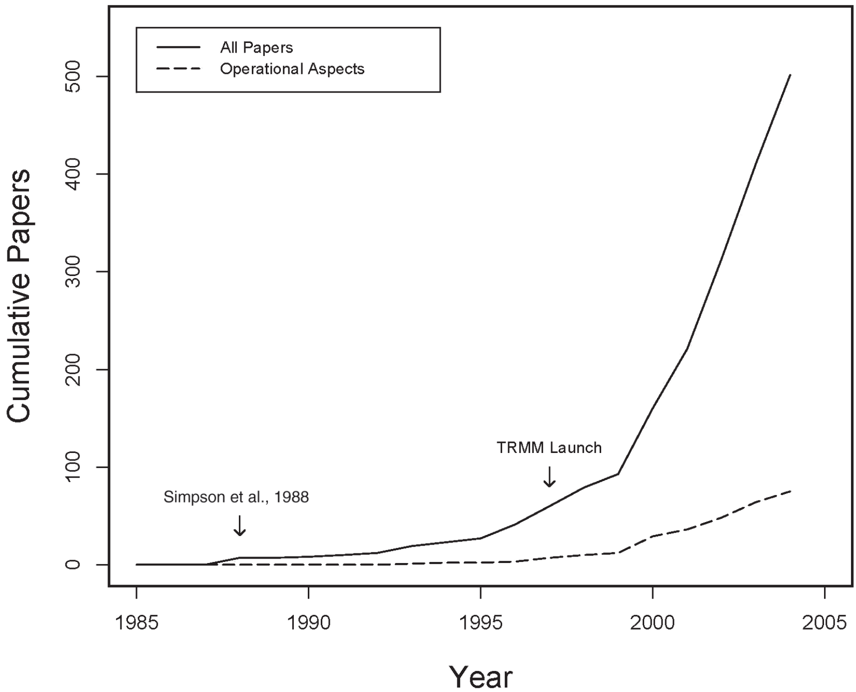

FIGURE 3-1 Evidence of a rapidly growing body of refereed publications directly related to TRMM. The data are obtained by searching the Institute for Scientific Information's Science Citation Index for papers that mention TRMM either in the title, abstract, or keywords. Papers dealing with operational aspects are based on terms such as "real-time," "operational," and "assimilation." SOURCE: Matthias Steiner, Princeton University.

EFFECT OF TRMM

One proxy measure of TRMM's effect on the scientific enterprise and technology development is the dramatically increasing number of refereed publications that mention TRMM (see Figure 3-1).[1] The TRMM launch triggered a flood of research that led to significant improvements in our understanding of tropical weather systems and their prediction, as well as quantification of key

[1]Note that the true impact of TRMM goes significantly beyond publications that specifically mention TRMM. Much research has been facilitated by TRMM support, but there is no reasonable way to grasp the full extent of TRMM's influence.

aspects of the hydrologic cycle and the climate system. The studies captured in Figure 3-1 span a broad spectrum of topics. They include contributions to increasing the basic scientific knowledge needed for future applications (e.g., descriptive and diagnostic studies) as well as operational applications (e.g., monitoring weather features, notably tropical cyclone activity, climate monitoring, numerical weather prediction and climate model development, and model assimilation of TRMM data in forecast operations). Operational applications of the emerging knowledge lag behind research applications (see Figure 3-1); however, operational use of the TRMM data has substantially increased as quality control issues have been resolved. Routine generation of TRMM data products started in 1998. Today TRMM data products can be accessed in real time on the Internet (Hawkins et al., 2001).

UNIQUENESS OF TRMM

TRMM has two unique attributes that make it ideal for observing tropical rainfall systems: (1) its suite of complementary observing instruments and (2) its orbital characteristics. In later sections of this and the next chapter, we differentiate between applications that use TRMM data only, or as the primary component of a research or operational activity (single asterisk), and those that use TRMM data as a complementary component of an operational or research activity (marked with a double asterisk).[2]

Uniqueness of TRMM Sensors

TRMM provides a complementary suite of active and passive sensors flown on a single platform providing a unique view of precipitation. Due to its complement of instruments, TRMM has been called a "flying rain gauge." The TRMM observing system employs the only precipitation weather radar in space (referred to as the Precipitation Radar, or PR). The PR provides the most direct method of observation of precipitation and its vertical distribution (i.e., enabling a three-dimensional view of precipitation). Efforts to resolve disagreements between precipitation estimates from the PR and TRMM Microwave Imager (TMI) are only now reaching the point where TRMM's potential to act as a global rainfall reference standard may be utilized. Without the PR in space, there will be no similar opportunity for calibration with an active sensor until the GPM core satellite is launched.

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[2]There is a gray boundary between these two categories, but the distinction serves as a first-order attempt to differentiate between essentially stand-alone contributions and complementary but still unique contributions of TRMM.

BOX 3-1
Using TRMM Data as a Global Reference for Precipitation Estimates

Use of TRMM data as the global reference against which data from spaceborne microwave sensors[a] are adjusted is the subject of ongoing research (Berg, 2004; Joyce et al., 2004; Ushio et al., 2004). The combination of TRMM's unique sensor suite and orbit underpins this approach.

In this approach, data from microwave sensors are compared with the TRMM PR or TMI data over 10- to 30-day intervals rather than for individual overpasses because of inherent fluctuations and differences at the single-overpass timescale. For added detail, the 10- to 30-day datasets are divided into latitude bins (e.g., 0 to 10 degrees, 10 to 20 degrees, etc.) and time bins (e.g., local midnight to 0300, local 0300 to 0600, etc.).

TRMM is the only satellite that collects precipitation data across all local times and can therefore populate all time bins. By comparison, SSM/I data can populate all 10-degree boxes but only at fixed local times. If AMSR-E were the reference instead of TRMM there would be no intersecting time boxes between SSM/I (channel F-15, for example) and AMSR-E because AMSR-E views at 1330 and 0130 local time and SSM/I views at 1030 and 2230 local time.

[a]TMI, SSM/I, AMSU-B, and AMSR-E—see Appendix J.

TRMM's Unique Orbit

TRMM's unique orbital characteristics enable it to fill temporal and spatial sampling gaps from all current and soon-to-be-launched weather-related satellite sensors (see Box 3-1). TRMM's 35-degree inclination, low altitude (402.5 km), and non-sunsynchronous[3] orbit provides multiple benefits when compared with the space and time sampling dictated by standard polar orbiting environmental satellite trajectories. The low-latitude orbit permits rapid updating in the tropical belt and the precessing nature of the orbit allows for sampling of the diurnal variation of precipitation. The ability to map and monitor rain at nonstandard viewing times (relative to the polar-orbiting satellites) permits a better understanding of rain event life cycles when combining TRMM data with visible, infrared, and passive microwave sensors on other satellites.

LONGEVITY AND STATUS OF TRMM SENSORS AND SPACECRAFT

Apart from the CERES sensor that failed after eight months, there are presently no indications of instrument, platform, or bus degradation; the TRMM

[3]A sunsynchronous orbit is one in which a satellite will always pass over the same point on Earth at the same local Sun time and at fixed time intervals. A non-sunsynchronous orbit means that the satellite passes over the same point at different local Sun times.

satellite and its PR, TMI, Visibile and Infrared Scanner (VIRS), and Lightning Imaging Sensor (LIS) sensors remain in excellent shape.[4] NASA Goddard Space Flight Center (GSFC) conducted an independent assessment of the TRMM spacecraft and instruments. GSFC studied the wear-out mechanisms and concluded that the probability of TRMM's life limited by various failure mechanisms such as radiation, atomic oxygen, or gyro failures through 2010 is "*very low*."[5] In a separate analysis of the PR, there was no indication that it is likely to fail in the near future.[6]

The reliability of the TRMM PR has not only demonstrated the feasibility of operating such technology in space but it has also demonstrated the potential of this technology for future operational systems.

The TMI, VIRS, and LIS sensors can fully operate at any altitude prior to a deorbit burn as long as the solar array is configured to provide sufficient sensor power.[7] The PR can only provide partial data during the descent if power is available because the sensor's attributes dictate specific altitude windows in which full data fidelity is possible. The PR's pulse repetition frequency and its need to fully sample the atmospheric column from the Earth's surface to approximately 18 km altitude create windows at approximately 50-km intervals in which the PR achieves full capability.[8] Thus, the original 350-km orbit and the current 402.5-km orbit are PR-optimized. The spacecraft can drift slightly up or down from these baseline altitudes and fully retrieve atmospheric rain profiles. However, when TRMM was permitted to go below 395 km during the summer of 2004, the sensor started to miss the highest rain tops near 18 km.[9]

CONTRIBUTIONS OF TRMM TO RESEARCH

The contributions of TRMM are divided into two categories: (1) climate and weather and (2) applied research that increases the knowledge base to enhance applications.

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[4]Presentations from Robert Adler, NASA, and Toshio Iguchi, National Institute of Information and Communications Technology, at the November 8 workshop.

[5]Briefing by John Deily, NASA, at NASA headquarters on March 26, 2004: A GSFC Independent Technical Assessment of Extended Life for the TRMM Spacecraft.

[6]Presentation by Toshio Iguchi at the November 8 workshop.

[7]This would probably not be the case if the arrays are realigned to give maximum drag if the decision to deorbit is made (Robert Adler, in presentation at the committee's November 8 workshop).

[8]We need the rain and surface return to be centered within the observation window—which is approximately 35 km. This 35-km window guarantees that the return contains the surface, some mirror-image, and the precipitation in a column at least 18 km above the surface. (A margin is needed because of the oblateness of the Earth and the slight eccentricity of the orbit and also changes in arrival time with incidence angle, all of which means that the precipitation return shifts position within the window depending on the latitude and incidence angle.) Source: Bob Meneghini, NASA, and Joe Turk, Naval Research Laboratory, personal communications, December 2004.

[9]Robert Adler at the November 8 workshop.

Climate and Weather

Many of the key TRMM achievements in climate and weather research fall in two basic categories that also include many if not most of the original science questions of TRMM. These are (1) fundamental new information on the synoptic climatology of tropical rainfall and weather systems and (2) a reliable benchmark climatology of the basic features of the tropical rainfall field.

Key "for-the-first-time" achievements in the first category include

- detailed vertical profiles of precipitation and latent heating* (Tao et al., 2004), [10]
- quantitative determination of the relative contributions of stratiform and convective precipitation* (Schumacher and Houze, 2003; Schumacher et al., 2004),[11]
- description of the fine-scale structure of rainfall systems that can be determined from the PR data* (Robertson et al., 2003), and
- documentation of lightning and convection relationships over land and ocean* (Toracinta et al., 2002).

Key achievements in the second category include

- for the first time, a definitive description of the diurnal cycle of precipitation over the oceans as well as the tropical land areas* (Nesbitt and Zipser, 2003),
- a reliable seven-year climatology of the mean annual tropical rainfall field** (Adler et al., 2003), and
- a seven-year mean annual cycle** that is far superior to that previously available (Adler et al., 2003).

The achievements in this second category result from the ability to produce redundant estimates of precipitation using different combinations of satellite sensors such as the PR and TMI.

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[10]Recall that we use a single asterisk to differentiate applications that use TRMM data only, or as the primary component of a research or operational activity, from those that use TRMM data as a complementary component of an operational or research activity (marked with a double asterisk).

[11]The TRMM PR is designed to record three-dimensional maps of precipitation reflectivity. Such measurements are unique because they yield information on the intensity and distribution of rain and its type, storm depth, and the height of the brightband. The rain type can be classified into convective and stratiform regions that can be described by different mean vertical motion distributions and growth mechanisms. Convective and stratiform regions have different heating profiles (Houze, 1997). A distinction between the two types of precipitation is critical because the latent heat release peaks at different levels. General circulation models are very sensitive to the profile of latent heating, especially in the tropics.

Other significant achievements include

- quantitative documentation of precipitation patterns** using TRMM data with other precipitation estimates to study interactive relationships between rainfall, sea surface temperature, synoptic systems (tropical cyclones), and climatic features;
- mapping sea surface temperature through clouds for improved climate records** (Stammer et al., 2003); and
- effect of pollution and other human influences on precipitation formation** (e.g., role of urban areas) and thus on the environment (Rosenfeld, 1999, 2000; Ramanathan et al., 2001; Rosenfeld et al., 2001; Andreae et al., 2004), a value-added scientific achievement not anticipated in the original TRMM mission plan.

Applied Research

Highlights of TRMM's contribution to applied research include

- a wealth of climatological and diagnostic information on tropical rainfall and associated underlying physical processes derived from analysis and diagnosis of the PR and TMI data* (Betts and Jakob, 2002);
- insight into the physical processes of precipitation formation:* the TRMM mix of sensors advances validation beyond simply comparing rainfall estimates to evaluating the underlying physical processes and how they are reflected in the observations. Before TRMM, the information that is needed for the development and validation of hydrologic components in weather and climate models was, for the most part, non-existent. TRMM data have, for example, exposed serious weakness in the representation and timing of convective precipitation in both weather forecast models and climate models;
- enhanced sea-surface-temperature nowcasting applications using TRMM TMI data** (Wentz et al., 2000; Gentemann et al., 2004);
- unique, fine-scale information on hurricane and typhoon structure* linked to rapid intensification (Kelley et al., 2004);
- calibration of long-term satellite precipitation dataset and multisatellite three-hour analysis** (Adler et al., 2000; Huffman et al., 2004);
- experimental tropical cyclone forecasts** that draw on quantitative precipitation climatology of tropical cyclones and the precipitation characteristics of tropical cyclones as a function of intensity, propagation speed, sea surface temperature, stage of El Niño-Southern Oscillation cycle, ocean basin, and other physical parameters;[12]

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[12]For instance, analysis of TRMM data has revealed asymmetries in the rain pattern with respect to the track resulting from wind shear in the lower atmosphere (F. Marks, NOAA, personal communication, November 2004).

- use of atmospheric moisture data derived by passive microwave imagers to understand tropical cyclone intensity** (Dunion et al., 2004);[13]
- integration of TRMM data into forecast model initialization procedures;**
- use of PR and TMI datasets by the International Precipitation Working Group to tackle research and operational satellite-based quantitative precipitation measurement issues and challenges** (see Appendix E);[14] and
- enhanced understanding of tropical cyclone inner eyewall dynamics* while monitoring eyewall replacement cycles (Hawkins and Helveston, 2004).

CONTRIBUTIONS OF TRMM TO OPERATIONS

Operational use of TRMM data has increased since this unique dataset became available in near real time in 1998. Applications fall into four groups: (1) tropical cyclone monitoring, (2) real-time rainfall estimation, (3) assimilation for improved numerical weather prediction, and (4) monitoring of climate variability (precipitation, sea surface temperature). Many organizations and individuals have invested in bringing TRMM data into the operational environment because of the unique aspects of TRMM's orbit and sensor suite. This reflects their professional judgment of the value of doing so based on their experiences of improvements in such things as fixing the location of tropical cyclones and estimating storm intensity (see Appendix K). Nonetheless, the effect of TRMM data on operational applications has not been widely quantified because the data record is too short for meaningful statistical analysis[15]

[13]Passive microwave imager data from TMI, SSM/I (Special Sensor Microwave/Imager), and AMSR-E (Advanced Microwave Scanning Radiometer for EOS [Earth Observing System]) are being used to map the total columnar water vapor distribution near tropical cyclones to monitor the impact of storms entraining dry, stable air. Dry, stable air from the Saharan Air Layer frequently emerges from West Africa and crosses the Atlantic Ocean with little modification. This very stable air mass greatly suppresses convective activity and can limit storm intensification and/or cause a storm to weaken if the Saharan air reaches the storm's inner core. Due to its superior spatial resolution, TMI can reveal fine details not seen in SSM/I data.

[14]The International Precipitation Working Group (IPWG) is cosponsored by the Coordination Group for Meteorological Satellites and the World Meteorological Organization. The second IPWG workshop was held in Monterey, Calfironia on 25-28 October, 2004, and highlighted many aspects of TRMM data as both a reference standard and as a multisatellite precipitation data product. Meeting reports and presentations can be found at http://www.isac.cnr.it/~ipwg/meetings.html.

[15]The 2001 NASA workshop (see Box 2-2) found the same lack of quantification of TRMM's impact. A sense of the order of magnitude of the impact of TRMM data on forecasts can be obtained from information provided to the committee by James Franklin of the National Hurricane Center in December, 2004. The improvement of hurricane track forecasts due to use of data from reconnaissance aircraft has been assessed quantitatively by comparing forecasts of storm center fixes (and the motion of the storm) with and without the aircraft data for similar geographical

and control experiments wherein the TRMM data are eliminated and the analysis reruns have not been done. Further, the socioeconomic effects on end-users of improved forecasts have not been quantified.[16] This section summarizes the primary operational uses of TRMM data by domestic agencies (at the National Oceanic and Atmospheric Administration [NOAA] and in the Department of Defense) and internationally.

NOAA's Operational Use of TRMM

NOAA Administrator Vice Admiral Lautenbacher's letter to NASA Administrator Sean O'Keefe demonstrates NOAA's need for TRMM observations (see Appendix H). Max Mayfield, Director of NOAA's National Hurricane Center, also expressed a desire for TRMM observations in a July *Washington Post* article.[17] To date, NOAA's operational usage of TRMM data has primarily focused on TMI data.

- *Monitoring hurricanes with TMI data at the National Weather Service's Tropical Prediction Center.* The Tropical Prediction Center in Miami uses near-real-time TMI data to help fix hurricane center positions (see Appendix K). Such positions are often poorly defined in routine visible and infrared imagery. The precision of these positions is important to current warnings and subsequent track forecasts. The Tropical Prediction Center also uses TRMM TMI data to help analyze the organizational structure of hurricanes. Knowing this structure can be crucial in estimating the maximum winds associated with a storm as well as in identifying possible rapid intensity change scenarios.

The TMI data are valuable for monitoring hurricanes (e.g., Box 3-2) because of their high spatial resolution both at 37 GHz and 85 GHz and the temporal gaps they fill by virtue of TRMM's precessing orbital path (Lee et al., 2002).

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areas. The accuracy improvements were 14 percent, 84 percent, and 44 percent over 24, 48, and 72 hours, respectively. Improvements due to TRMM data are likely less than this, since TRMM data are less exact and are not obtained as frequently near landfall of the storms (but instead are available further away from the U.S. territories). More time and a longer data record are needed for a similar quantitative study of the improvements in hurricane track forecasts due to TRMM data. As a further aside, storms encountering the U.S. Gulf Coast can be sampled by four consecutive TRMM orbits, meaning the time sampling is as good or better than aircraft sampling, though not as accurate.

[16]NOAA has attempted to provide estimates for the GOES-R satellite now in the planning stages. This could be done for TRMM data as well, using a similar methodology (NOAA/NESDIS, 2002).

[17]" 'A lot of times you'll just see a ball of white cloud, but TRMM can go to the core, see the eyewall start to develop: Is it intensifying? Is it getting better defined? Is it falling apart?' . . . National Hurricane Center Director Max Mayfield said in a telephone interview from his Miami office." Quoted in Gugliotta (2004).

BOX 3-2
Examples Using TRMM TMI Data for Monitoring Hurricanes

National Hurricane Center advisories use TMI data to help fix the storm location for real-time warnings. These advisories include specific reference to the effect of TMI data on the center's understanding of storm location and/or intensity trends. For example, a Hurricane Isaac advisory on September 27, 2000 noted "A TRMM OVERPASS AT 0259Z FROM THE [Naval Research Laboratory] WEB PAGE SHOWED THAT ISAAC HAS DEVELOPED A NEW EYEWALL . . . AT 45 NM IN DIAMETER CONSIDERABLY LARGER THAN THE ONE IT HAD A COUPLE DAYS AGO." In another example, from October 26, 2000, use of TMI data for Tropical Storm Paul was discussed: "A TRMM OVERPASS AT 08Z PLACED THE CIRCULATION CENTER VERY CLOSE TO THE EDGE OF THE DEEP CONVECTION."

In particular, the more frequent views afforded by TMI overpasses, when combined with other microwave sensors, aid monitoring of a storm's intensity fluctuations. The TRMM data are particularly important for monitoring storms in the East Pacific basin, where there are few reconnaissance aircraft observations.

• *Rainfall estimates for flood forecasts using TMI data at the National Environmental Satellite, Data, and Information Service Satellite Analysis Branch.* The Satellite Analysis Branch uses TMI to augment other sources of data to their real-time, operational rainfall estimation algorithm. TMI gives substantial value in this Tropical Rainfall Potential forecast system due to its high resolution.[18] The rainfall estimates are used as guidance by the National Weather Service for flood forecasts and warnings.

• *Numerical weather prediction using TMI at the National Centers for Environmental Prediction (NCEP).* NCEP has been assimilating TRMM data into its global numerical weather prediction system since October 2001.[19] Although the effect of including TMI on model forecast skill scores is less than some of the other satellite data types (e.g., data from the Advanced Microwave Sounding Unit and winds from the geostationary orbiting satellites), there is evidence of modest improvements, especially in the tropics.[20]

• *Air traffic advisories using the TRMM LIS.* Lightning data are used for aircraft routing across oceans by the Aviation Weather Center at NCEP. Forecasters responsible for convective SIGMETs (significant meteorological adviso-

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[18]R. Ferraro, NOAA, personal communication, November 2004. Figure shown by F. Marks at November 8 workshop.

[19]Personal communication from Stephen Lord, NOAA, November 2004.

[20]Presentation by Stephen Lord, NOAA, at the November 8 workshop.

ries) that are of concern to planes routinely use LIS data by overlaying them with conventional visible and infrared imagery to better understand which convective cells have increased likelihood of turbulent weather. The International Operations Branch, specifically the Tropical Desk, use LIS data to monitor convection for international SIGMET decision making over the northwest Atlantic and central and northeastern Pacific, as well as for forecasting in the Gulf of Mexico, Caribbean, and southwest Atlantic.[21]

- *Climate monitoring of monthly and seasonal global precipitation variability by the Climate Prediction Center*. The Climate Prediction Center uses TMI data, which provides high spatial resolution due to its low orbit, as the reference standard for adjusting data from other passive microwave sensors (Joyce et al., 2004).
- *Use of TMI sea surface temperature retrievals in analyses at the National Climatic Data Center*. This is a routinely prepared analysis product for climate monitoring and sea surface temperature boundary conditions for operational weather forecasts (Reynolds et al., 2004).
- *Near-real-time use of TMI sea surface temperatures by the Tropical Prediction Center to help map cold wakes created by tropical cyclones*. TMI can "see" through clouds obscuring infrared sensors and detect sea surface temperatures including cold wakes that can negatively affect intensity of following storms due to decreased moisture flux into the tropical cyclone heat engine.[22] Surface cooling occurs over larger areas than can be monitored by in situ measurements such as airborne expendable bathythermographs. Thus, spaceborne sensors are critical for mapping such phenomena. Furthermore, microwave imagers like TMI with low-frequency channels (5 and 10 GHz) enable near-real-time mapping even in the turbulent tropical cyclone environment.

Department of Defense's Operational Uses of TRMM

- *Monitoring tropical cyclones using TMI at the Joint Typhoon Warning Center (JTWC)*. The JTWC in Pearl Harbor, Hawaii, uses TMI data to help fix the location of tropical cyclones in the western Pacific Ocean, Indian Ocean, and Southern Hemisphere oceans.[23] JTWC has used TMI data served through the

[21]Personal communication from Carolyn Kloth, Aviation Weather Center, NOAA, November 2004.

[22]Upwelling can reduce sea surface temperature by 1-6°C.

[23]For example, "On several occasions TRMM passes over a [tropical cyclone] led to storm relocation and changes in intensity for our typhoon warnings" (Lt Col Amanda Preble, Director, JTWC, 2004). Additionally, "TRMM data has helped JTWC increase its lead-time from 24 hours to over 41 hours" (Peter Furze, Commanding Officer, Naval Pacific Meteorology and Oceanography Center/JTWC). Source: Robert Adler, NASA.

BOX 3-3
Examples Using TMI Data Referenced in Joint Typhoon Warning Center Warning Discussions

Low-level wind shear during Typhoon Shanshan on September 23, 2000: "REMARKS: 232100Z8 POSITION NEAR 31.0N4 170.1E9. TYPHOON (TY) 26W (SHANSHAN) . . . A 231342Z5 TROPICAL RAINFALL MEASURING MISSION (TRMM) PASS DEPICTS AN EXPOSED LOW LEVEL CIRCULATION WITH CONVECTION TO THE NORTH."

Small-scale eyewall changes during Super Typhoon Bilis: "221500Z0 POSITION NEAR 22.8N2 121.4E8. SUPER TYPHOON (STY) 18W (BILIS) . . . A 221009Z4 TROPICAL RAINFALL MEASURING MISSION MICROWAVE IMAGE DEPICTED A CONCENTRIC EYE WALL WITH SPIRAL CONVECTIVE BANDS WRAPPING INTO THE CENTER OF THE SYSTEM."

Naval Research Laboratory and Fleet Numerical Meteorology and Oceanography Center (FNMOC) tropical cyclone Web pages since 1998. Since 1999, JTWC has processed and displayed TMI data internally (Lee et al., 1999). The center relies on satellite-based observations more than NOAA's Tropical Prediction Center because routine reconnaissance aircraft missions do not exist outside the Atlantic basin. Indeed, approximately 16 percent of all position fixes made by JTWC in 2004 were from the TRMM data.[24]

In particular, JTWC uses TMI data to

1. identify when wind shear exposes low-level circulation features (TMI data are used to monitor a tropical cyclone's low-level circulation center that is hard to track when strong winds aloft shear away the upper-level convective clouds and leave only the lower and warmer clouds [e.g., Box 3-2]; these low-level clouds often have a small temperature contrast with the background sea surface temperatures and are thus hard to distinguish in coarse resolution geostationary night time infrared imagery),
2. detect small-scale eyewall changes indicative of cyclone intensity fluctuations (e.g., Box 3-3, Figure 3-2),
3. fill in temporal gaps created by all polar orbiting environmental satellite sensors, and
4. obtain frequent views of storms on three or four consecutive orbits when the storms move through the 32- to 37-degree belts north and south of the Equator.

[24]Presentation by Jason Ronsse, JTWC, at the November 8 workshop.

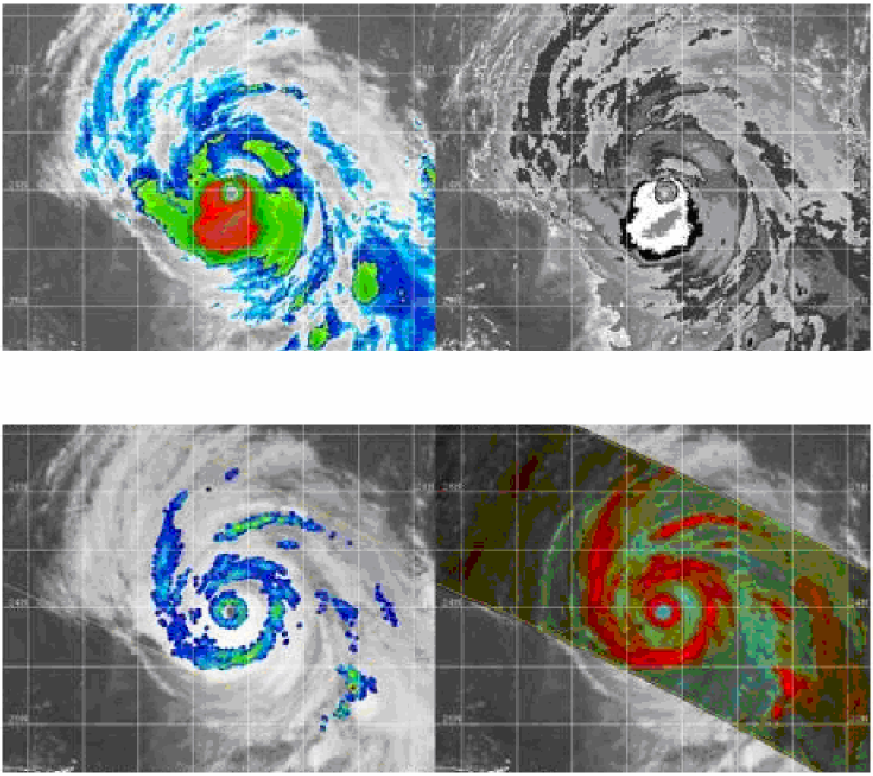

FIGURE 3-2 Illustration of the multiple hurricane eyewalls and rainbands revealed in the microwave (TMI) that are not viewable in infrared (in this case for Hurricane Gert in 1999). Top left: GOES infrared image. Top right: GOES infrared image, Dvorak enhancement. Bottom left: TMI polarization corrected temperatures overlain on GOES infrared. Bottom right: TMI 85 GHz "color" composite image with GOES infrared outside of TMI swath. SOURCE: Naval Research Laboratory Tropical Cyclone Web Page Team.

• *Tropical cyclone monitoring at the Air Force Weather Agency*. The Air Force Weather Agency's Omaha, Nebraska, tropical cyclone satellite fixing center has used TMI data since 1998 because of TMI's ability to see through non-raining upper-level clouds. The agency provides near-real-time tropical cyclone fixes globally to JTWC; NOAA's Tropical Prediction Center, Satellite Analysis Branch, and Tropical Satellite Analysis Branch; the Central Pacific Hurricane Center; and the Navy's regional center at Norfolk, Virginia.

- *Rainfall estimation using PR and TMI at the Naval Research Laboratory.* TRMM PR and TMI data are used in the Naval Research Laboratory's merged rainrate method. This method also incorporates cloud-top temperatures from five geostationary imagers (GOES-EAST/WEST, GOES-9, and Meteosat-5/7). The rainrate product has been used by several operational forces, including those in Operation Iraqi Freedom (Turk et al., 2002, 2003; Miller et al., 2004).

International Uses of TRMM

Tropical Cyclone Forecasting

Numerous agencies worldwide, including the six World Meteorological Organization Regional Specialized Meteorological Centers (Japan Meteorological Agency, India Meteorological Center, Meteo France, NOAA's National Hurricane Center and Central Pacific Hurricane Center, and the Fiji Meteorological Service) are using TMI data in an operational mode for tropical cyclone analysis. In addition, the tropical cyclone warning centers in Australia and New Zealand routinely incorporate TMI data in their tropical cyclone forecasting. Indeed, at the 2002 International Workshop on Tropical Cyclones in Cairns, Australia, presenters from many countries indicated they routinely incorporated TMI imagery into their operations (see Elsberry and Velden, 2003). These data are served through tropical cyclone Web pages introduced by the Naval Research Laboratory and tranferred to the Fleet Numerical Meteorology and Oceanography Center. For some presenters, this workshop marked the first time they became aware of the Website and the data it serves.

The data are used for detecting location and intensity of tropical cyclones because of their high spatial resolution combined with the capability of the 37-GHz channel to resolve tropical cyclone eyewall features and their temporal gap-filling attributes.

The Japan Meteorological Agency (JMA) uses both internally generated TMI and PR products as well as TMI data from the Naval Research Laboratory/FNMOC for analysis of typhoons approaching Japan. The Naval Research Laboratory receives email from JMA and other World Meteorological Organization centers when its tropical cyclone Web page temporarily goes offline, emphasizing the near-real-time need that TRMM data fulfills.

Numerical Weather Prediction

JMA and the European Centre for Medium-Range Weather Forecasts (ECMWF) have led the way in using TRMM data in numerical weather prediction. JMA is assimilating TMI observations into its global model and ECMWF has conducted a series of near-real-time experiments with its 4-DVAR operational forecast system and plans to go fully operational with the TRMM data assimilation pending the decision to extend the TRMM mission.

Precipitation "Nowcasting"

Many countries are now creating and distributing nowcast rain products and serve a host of users including hydrologists, farmers, weather forecasters, numerical modelers, the military, and the climate community. For example, rainfall analyses that capture extensive rain events or rain over specific flood-prone geographic regions[25] are being used in near real time to create weather hazard warnings that guide the evacuation of people and resources. These rain datasets are being incorporated into hydrological surface runoff models to predict rapidly changing downstream effects (Lee and Anagnostou, 2004).

Nowcast rain products are undergoing extensive validation against ground truth rain gauges, radar, and combined precipitation datasets. And nowcasting has reached new levels of fidelity by incorporating microwave remotely sensed data. Earlier infrared-only algorithms were limited by the poor correlations between cloud-top temperatures and actual rainfall and thus physical retrievals using passive microwave imagers such as SSM/I and TMI data brought greater accuracy. However, microwave imagers do not provide the temporal sampling required for rapidly changing rain events. Consequently, "merged" infrared-microwave techniques evolved, and infrared data from geostationary satellites are trained using microwave imagers. The TRMM PR rainrate data serve as the cross-calibration source for both. Hence, the PR rainrate measurements are crucial for enhancing the accuracy of the final merged rainrate product: they are the key factor in deriving accurate global and mesoscale rain analyses.

OPERATIONAL COMMUNITY JUST BEGINNING TO ADOPT PR DATA

It is evident from the previous section that TMI data currently fill the great majority of operational uses of TRMM data. The operational community has not been able to make extensive use PR data because of

- the data having only recently become available in near real time to the broader community outside of NASA and JAXA,

[25] See, for example, NASA's TRMM Website (http://trmm.gsfc.nasa.gov/) and especially the page alerting users to potential flooding areas (http://trmm.gsfc.nasa.gov/publications_dir/potential_flood.html).

- the new and unique nature of the PR data and the learning required to exploit them,
- the perceived experimental nature and finite lifetime of the PR, and
- the lack of sophistication in the representation of cloud and precipitation physics in current operational forecast models and global climate models that prevents them from taking advantage of the native resolution of the PR data.[26]

Cloud-resolving models that are currently under development will require the PR data in order to develop and validate the high-resolution model physics.[27]

FINDINGS

NASA and JAXA are to be commended on the highly successful TRMM satellite whose achievements and longevity have exceeded even the optimistic expectations at the time of launch. These agencies are also to be commended for their visionary actions to extend the lifetime of TRMM beyond the original anticipated maximum length of the mission thereby enhancing the value of the data from TRMM to science and operations.

FINDING 3.1: TRMM has two unique attributes that make it ideal for observing tropical rainfall systems: (1) its suite of complementary observing instruments and (2) its orbital characteristics.

- The PR is the only precipitation radar in space and provides direct, fine-scale observations of the three-dimensional structure of precipitation systems. The combination of PR and LIS observations provides a measure of convective intensity.[28] The combination of PR, TMI, and VIRS observations from the same platform serves, in effect, as a "Rosetta Stone" for cross-calibration of the indirect estimates of precipitation from microwave, visible, and infrared observations.
- The TRMM orbit (low-altitude, non-sunsynchronous, precessing, 35-degree tropical inclination) provides sampling in the tropics that is far more frequent, and far more spatially comprehensive, than that obtained from standard polar orbiter satellites.

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[26]Comments of Taroh Matsuno, Japan Agency for Marine-Earth Science and Technology, at the November 8 workshop.

[27]Ibid.

[28]TMI data can also gauge convection, but the PR and LIS data are principally used for this.

FINDING 3.2: TRMM has achieved its original science goals and produced a greater than expected range of scientific results in

1. climate and weather research (e.g., a reliable seven-year climatology of the mean annual tropical rainfall and its interannual and diurnal cycles; fundamental new information on the synoptic climatology of tropical weather systems, e.g., the first detailed precipitation and latent heating profiles throughout the tropics and subtropics, first detailed convective and stratiform rainfall structure, and a description from space of the fine-scale structure of rainfall systems that can only be determined from the PR data; understanding of how sea surface temperature (SST) patterns modify precipitation through air-sea interaction; quantitative documentation of precipitation patterns; mapping sea surface temperature through clouds for improved climate records; demonstrating the effect of pollution and other human influences on precipitation formation); and
2. applied research (e.g., a wealth of climatological and diagnostic information on tropical rainfall; insight into the physical processes of precipitation formation; unique, fine-scaled information on hurricane and typhoon structure linked to rapid intensification; calibration of a long-term satellite precipitation dataset and multisatellite three-hour analyses; experimental tropical cyclone forecast methods; enhanced SST nowcasting applications using TRMM TMI data; integration of TRMM data into forecast model initialization procedures; enhanced understanding of tropical cyclone inner eyewall dynamics and tropical cyclone intensity).

FINDING 3.3: Since 1998, TRMM has provided near-real-time information for operational purposes. Data from the TMI sensor are most often used. There are four principal applications: (1) monitoring and predicting the future behavior of tropical cyclones, (2) estimating rainfall, (3) predicting weather, and (4) monitoring of climate variability (precipitation and sea surface temperature). Many organizations and individuals have invested in bringing TRMM data into the operational environment because of the unique aspects of TRMM's orbit and sensor suite. This reflects their professional judgment of the value of doing so based on their experiences of improvements in such things as accuracy of center fixes for tropical cyclones and prediction of storm intensity. Nonetheless, the effect of TRMM data on operational applications has not been widely quantified because the data record is too short for meaningful statistical analysis and no one has done control experiments wherein the TRMM data are eliminated and the analysis is rerun. Further, the socioeconomic effects on end-users of improved forecasts have not been quantified.

In the United States TRMM data are used in operations by organizations in NOAA (e.g., Tropical Prediction Center, NCEP, Satellite Analysis Branch, Aviation Weather Center, Climate Prediction Center, National Climate Data Center) and the Department of Defense (e.g., JTWC, Air Force Weather Agency, FNMOC, and the Naval Research Laboratory). In addition, TRMM data are used internationally for operations by World Meteorological Organization centers throughout the tropics for monitoring and forecasting tropical cyclone activity. Furthermore, groups in Japan and Europe have begun using TRMM data in numerical weather prediction models. Because TRMM data are already being used operationally (which does not fit with NASA's primary focus of research and exploration), NASA has sought partnerships with other agencies to fund extension of TRMM. Thus, determining the future of TRMM has become a multi-agency issue.

FINDING 3.4: The TRMM satellite and its sensors remain in excellent condition. There is every reason to believe that they will continue to operate well for the next few years.

FINDING 3.5: TRMM's potential to help improve forecasts—especially through increased use of PR data in models—has not been fully realized because of

- the PR data having only recently become available in near real time to the broader community outside of NASA and JAXA,
- the new and unique nature of the PR data and the learning required to exploit them,
- the perceived experimental nature and finite lifetime of the PR, and
- the lack of sophistication in the representation of cloud and precipitation physics in current operational forecast models and global climate models such that they cannot yet take advantage of the native resolution of the PR data.

4

Anticipated Contributions of TRMM

INTRODUCTION

The Tropical Rainfall Measuring Mission (TRMM) has exceeded its original mission goals. The TRMM objectives and goals, however, evolve as more is learned about how to make use of TRMM data—on their own as well as integrated with other observations and numerical weather prediction and cloud-resolving models. For example, learning from peculiar differences in how TRMM Microwave Imager (TMI) and precipitation radar (PR) observe weather systems and estimate rainfall around the globe and during various phases of the El Niño-Southern Oscillation (ENSO) cycle have yielded new ideas about the physical processes of precipitation formation, but many more observations need to be gathered to fully sample the many possible conditions and dependencies of cloud and weather systems on external conditions. These include large-scale atmospheric circulation and sea surface temperature patterns of warm and cold water, monsoon and ENSO structures, and orographic effects to name a few.

Extending TRMM operations beyond 2004 offers broad opportunities for advancing the operational and scientific uses of TRMM data. The value of acquiring new data for future operational applications and learning from existing TRMM data is obvious. This is also the case for many research applications.

This chapter is organized to address two of the committee's tasks: (1) to consider the expected operational and research contributions if TRMM is continued and (2) to assess the expected benefits of continuing TRMM operations until (a) the fuel is depleted to the level still needed for a controlled reentry, and (b) until all fuel is depleted. The key benefits of an extension of TRMM are summarized in Table 4-1. The table is divided into two columns. The left-hand column summarizes anticipated contributions from extending TRMM up to the fuel point when a controlled reentry is still possible. The right-hand column summarizes the anticipated additional contributions of extending TRMM beyond the fuel point (i.e., *supplementing* what is gained up to the fuel point). In addition, the expected contributions are separated into anticipated research and operations contributions. The elaborations in this chapter, working from the specific to the general, mirror the outline of Table 4-1.

ANTICIPATED CONTRIBUTIONS WHEN CONTROLLED REENTRY IS STILL POSSIBLE

Anticipated Operational Contributions

Another Year of PR and TMI Data for Tropical Storm Monitoring and Forecasting

Another year's worth of TMI and PR data would be valuable to the National Oceanic and Atmospheric Administration (NOAA) and recipients of its forecasts for the same reasons expressed by Vice Admiral Lautenbacher to Dr. Sean O'Keefe in 2004 (see Appendix H). Similarly, Department of Defense agencies, other agencies around the world (refer to Chapter 3), and their users will continue to benefit from the data.

TABLE 4-1 Anticipated Operational and Research Contributions due to Extending TRMM to the Fuel Point (approximately December 2005) and Beyond

Anticipated Contributions of TRMM Up to the Fuel Point (when controlled reentry is still possible)	Additional Anticipated Contributions of TRMM Beyond the Fuel Point (i.e., in addition to what is gained up to the fuel point)
OPERATIONS	OPERATIONS
• Another year of TMI and PR data for tropical storm monitoring and forecasting**	• Technology demonstration of the endurance of the first precipitation radar inspace*
• Another year of TMI data for numerical weather prediction**	• Improved forecasts from the operational assimilation of PR and TMI data into weather and climate prediction models**
• Another year of PR and TMI data for enhancing near-real-time rainfall products**	
• Another year of lightning data for air traffic advisories*	
• Realizing the potential to use PR as a global rainfall reference standard*	

TABLE 4-1 Continued

Anticipated Contributions of TRMM Up to the Fuel Point (when controlled reentry is still possible)	Additional Anticipated Contributions of TRMM Beyond the Fuel Point (i.e., in addition to what is gained up to the fuel point)
RESEARCH • Overlap with CloudSat radar operations and the A-Train satellite series** • Overlap with the Coriolis WindSat sensor** • Unique opportunities to enhance field experiments (TCSP, TEXMEX-II)** • Unique opportunities to enhance international research programs (GEWEX, THORPEX, Hurricane Field Program)** • TRMM's Precipitation Radar provides a calibration reference for the current GPM mission-like constellation of microwave satellite sensors** • TRMM is a catalyst for tropical cyclone research (e.g., research on convective bursts, tropical cyclone eyewall replacement cycles, improved forecasting of inland flooding during hurricanes)** • Longer TRMM record needed for tropical cyclone forecasting* • Longer TRMM record needed for climate research* • Foster improving moist physics parameterization for climate models, numerical weather prediction, and related assimilation systems by evaluating models of clouds and precipitation physics*	RESEARCH • Unique opportunities to enhance field experiment (AMMA)** • Developing the next generation hurricane forecast model** • Seamless transition into the Global Precipitation Measurement (GPM) mission* • Realization of a prototype GPM-like operation* • Avoiding researchers being ill-prepared for GPM** • Better characterization of interannual variability and the El Niño-Southern Oscillation cycle*

NOTE: See Appendix J for acronym definitions for field experiments and programs. We use a single asterisk to differentiate applications that use TRMM data only, or as the primary component of a research or operational activity, from those that use TRMM data as a complementary component of an operational or research activity (marked with a double asterisk). There is a gray area between these two categories, but the distinction serves as a first-order attempt to differentiate between essentially stand-alone contributions and complementary but still unique contributions of TRMM.

Another Year of TMI Data for Numerical Weather Prediction

In addition to the focused benefits of TMI data for tropical cyclone intensity forecasting and center fixing, the radiances detected by the TMI sensor are used to initialize tropical precipitation in global models. Furthermore, information from TMI on sea surface temperature and precipitation is used for numerical weather prediction.

Another Year of PR and TMI Data for Enhancing Near-Real-Time Rainfall Products

Continued availability of TRMM data will enable continued production of high-quality near-real-time and research three-hour precipitation analyses. TRMM data are used to calibrate other satellite information, with PR data as a key building block and TMI data to fill in temporal gaps. The fact that TMI is coincident with PR data gives an excellent time and space match, and correlations between TMI brightness temperatures and PR retrievals are better than matches with any other sensor due to the fast temporal changes in rain characteristics.

Another Year of Lightning Data for Air Traffic Advisories

Lightning data from the Lightning Imaging System on TRMM are used for aircraft routing over the world's oceans.

Realizing the Potential to Use PR as a Global Rainfall Reference Standard

The use of TRMM data as the global reference against which data from spaceborne microwave sensors are adjusted is the subject of ongoing research. The combination of TRMM's unique sensor suite and orbit underpins this approach.

Anticipated Research Contributions

Overlap with CloudSat Radar Operations and the A-Train Satellite Series

CloudSat is an experimental satellite that will use radar to measure the vertical structure of clouds and cloud properties from space including some characteristics of precipitation.[1] CloudSat will fly in formation with other satellites referred to as the "A-Train." This constellation comes into formation with the launch of CloudSat and CALIPSO in mid-2005. Combining the observations of

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[1]See http//www.cloudsat.atmos.colostate.edu.

the different sensors of the A-Train will provide an unprecedented view of clouds, aerosol, and precipitation (to a lesser degree) and the relationships between them. TRMM will add value to the A-Train observations of clouds and precipitation and to the science of the A-Train which seeks to address the effect of pollution and aerosols on precipitation.

Because the TRMM and CloudSat mission satellites both carry a radar, albeit with differing wavelength, the opportunity to have measurements by both radars simultaneously over a substantial amount of time will provide a basis for statistical comparison and cross-referencing. Statistical comparison offers a way of calibrating the information on tropical precipitation provided by CloudSat on the one hand and the possibility on the other hand of extending the capability of the PR to the extratropics and higher latitudes through the CloudSat radar. In addition, such a combined dataset would yield a direct measure of the percentage of the light precipitation that has been below TRMM's measurement threshold. This is important for Global Precipitation Measurement algorithm development, in particular through validation of these algorithms for higher-latitude precipitation.

Overlap with Coriolis WindSat Mission

The Coriolis WindSat polarimetric radiometer's launch in January 2003 produced the next step in spaceborne passive microwave radiometers. The WindSat sensor measures multiple polarizations not captured by previous microwave imagers such as SSM/I and TMI that enable the retrieval of all four Stokes vectors. This capability permits the extraction of the ocean surface wind speed and direction (vector), a major parameter for both meteorological and oceanographic nowcasting and forecasting (Gaiser et al., 2004).

The WindSat wind vector calibration and validation team has just completed their initial studies and a six-month digital dataset has been released to the scientific user community. WindSat is the risk reduction pathfinder for the upcoming (2009) National Polar-orbiting Operational Environmental Satellite System's Conical Scanning Microwave Imager/Sounder (CMIS) sensor that will be the main wind vector instrument for the next several decades. Using the PR data to help understand rain effect on WindSat wind vector retrievals will further CMIS efforts, since no planned satellite will have joint WindSat, CMIS, and PR capabilities on one platform.

Numerous cross-validation efforts are envisioned since WindSat and TMI channels are nearly identical except for the enhanced polarization on WindSat. WindSat and CMIS rainrate algorithms will directly benefit from having PR data available.

Unique Opportunities to Enhance Field Experiments

Unique opportunities exist in 2005 (and beyond) for the TRMM mission to enhance atmospheric field campaigns. For example, the National Aeronautics and Space Administration (NASA) is planning a major field experiment to support the Tropical Cloud Systems and Processes (TCSP) initiative in 2005. The TCSP campaign will include the NASA DC-8 and ER-2 aircraft in addition to many other facilities supported by NOAA and the National Science Foundation. This program will investigate tropical cloud systems and their environmental feedback. The initiative seeks innovative approaches that use NASA's observational data for investigations of tropical cyclones, the effect of cirrus clouds on atmospheric cycles of water and energy, and related feedbacks on the radiative, compositional, and dynamic attributes of the upper troposphere and lower stratosphere. The initiative also addresses the use of this knowledge in facilitating the development and evaluation of models and data assimilation systems that include representations of tropical cloud processes and their effect on Earth's climate system.

NASA's Earth Science Enterprise has sponsored a series of field experiments under the title CAMEX (Convection and Moisture Experiment) during the last several years to study rainfall and water vapor properties of the atmosphere. The third and fourth field missions of the series, conducted in 1998 and 2001 respectively, were focused more specifically on the study of tropical cyclone (hurricane) development, tracking, intensification, and landfalling effects using NASA's aircraft, space, and surface remote-sensing instrumentation. A noteworthy accomplishment of the most recent CAMEX has been a successful collaboration with NOAA and the U.S. Weather Research Program to address common research goals. The next experiment is planned as part of TCSP in 2005 and will continue to address the key research questions of the NASA Earth Science Enterprise while also making the best use of that program's assets. The emphasis of this experiment will be hurricane genesis and associated environmental processes. Other elements will include satellite calibration activities and collaborative research with the radiation physics community. There will be several opportunities for close coordination of the field campaign observations with direct overpasses if TRMM is still operational.

Unique Opportunities to Enhance International Research Programs

TRMM data enhance international programs such as the World Climate Research Program's Global Energy and Water Cycle Experiment (GEWEX) and World Meteorological Organization's THORPEX (The Observing-System Research and Predictability Experiment). GEWEX and THORPEX are existing international programs that aim to better observe and understand Earth's atmospheric system processes. The primary objective of GEWEX is to observe and model the hydrologic cycle and energy fluxes in the atmosphere. The primary objective of THORPEX, a global atmospheric research program, is to accelerate improvements in the accuracy of 1- to 14-day weather forecasts for the benefit of society and the economy. The observational components of both GEWEX and THORPEX will rely heavily on satellite-based measurements. TRMM, with its unique capabilities, could make an important contribution to such aspects as calibration of the 25-year record of satellite passive microwave and infrared data that is part of GEWEX. Many other potential contributions are listed in a July 6, 2004 letter from the World Climate Research Program to NASA and JAXA (see Appendix E).

TRMM's Precipitation Radar Provides a Calibration Reference for the Current GPM-like Constellation

The combination of TRMM's TMI and PR with the microwave sensors on other satellites provides many of the key elements of a Global Precipitation Measurement constellation concept. Now is the golden era of passive microwave satellite instruments, with nine currently in orbit (see Figure 4-1). The scientific

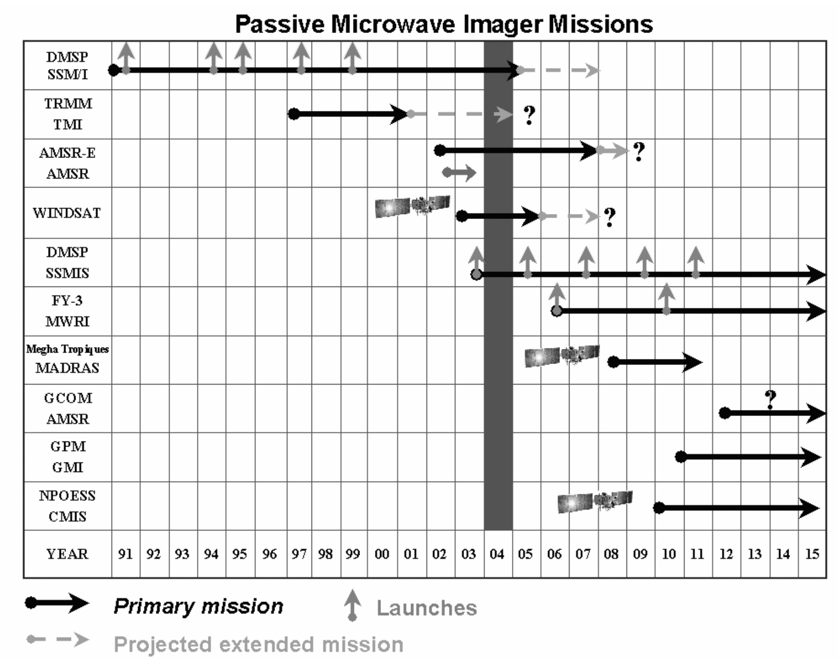

FIGURE 4-1 Duration of primary missions of spaceborne passive microwave imagers and their potential extensions (see Appendix J for explanations of program name abbreviations). For an updated version of this figure, see the companion report on GPM (NRC, in review).

and operational weather and climate communities have a fortuitous confluence of missions that have placed or will soon place microwave sensors in space. Data from the PR provide the calibration reference point for the entire constellation thereby enhancing the data products from all constellation sensors.

Extending TRMM would continue its role as a reference instrument. Extension also would allow NASA, NOAA, Department of Defense agencies, and foreign weather and space agencies to further experiment with integrating and merging data from these sensors with data from terrestrial sensors.

TRMM is a Catalyst for Tropical Cyclone Research

Data from TRMM have stimulated advances in tropical cyclone research and understanding. Summarized below are three areas of ongoing research that will benefit from extending TRMM.

- *Convective bursts*. TRMM's ability to reveal the characteristics of a cloud or cloud system with active precipitation, and to highlight these differences from location to location throughout the tropics, has underscored our lack of understanding of cloud physics on a number of scales.[2] The connection between convective bursts and tropical cyclogenesis and intensity changes is an active research topic in cloud physics. The PR is the only space-based method for quantifying the vertical structure of these convective systems. Fully characterizing and understanding the relationship between these convective bursts and tropical cyclone variability will require a longer record than is currently available, given the temporal and spatial coverage of TRMM.[3] Without PR no space-based near-real-time observations of the convective bursts (and the applicability of these observations to forecasting) will be available for the rest of the decade. Furthermore, the lightning sensor on TRMM adds insights into the intensity of convection, especially over land, where lightning is more often associated with deep clouds. This is a new resource for convection and storm research that would also benefit from a longer record.
- *Tropical cyclone eyewall replacement cycles*. Passive microwave imagers such as TMI can view tropical cyclone inner-core structure often obscured by upper-level clouds and thus masked in visible and infrared imagery. Intense tropical cyclones typically have a central dense overcast expanding from the central eyewall outward, sometimes clouding over the eye as well. These clouds make it difficult to view the eyewall replacement cycle, which is a key factor in storms with intensities at or above 120 knots (Hawkins and Helveston, 2004).

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[2]Presentation by Ed Zipser, University of Utah, at November 8 workshop.
[3]Ibid.

Microwave imagers, especially TMI, provide the means to observe the eyewall shrink as the storm intensifies, the formation of an outer eyewall, the collapse of the inner eye as moisture and momentum flux is constricted by the outer eyewall, and the shrinking diameter of the outer eyewall as the process begins anew (Velden et al., 2003). The TMI's unique qualities of temporal gap filling and high spatial resolution have enabled an improved understanding of this basic tropical cyclone dynamical feature that is now the subject of intense study.[4]

- *Improved forecasting of inland flooding during hurricanes*. Models that forecast hurricane-induced inland flooding are still in their infancy. Data from the PR and TMI sensors would help improve these forecasts and assist public officials to mitigate the effects of damage from high winds, storm surges, and inland flooding resulting from hurricanes (Williamson et al., 2002). This is especially true for countries with little observational infrastructure or coastal areas with little upstream information. Furthermore, continuing the flow of data from TRMM would allow policymakers to assess the socioeconomic value of these data in saving lives and improving the U.S. economy. Extending TRMM's mission will also allow weather modelers and forecasters to quantify the operational benefits of using PR and TMI data.

Longer TRMM Record Needed for Tropical Cyclone Forecasting

A longer record is required to collect enough examples to cover the parameter space of synoptic variability of tropical cyclones more fully. Over the first six years of TRMM data, the TMI instrument passes within 750 km of storm centers during one of every eight orbits, whereas PR observes within 250 km of the center during one of every 25 orbits.[5] The narrow swath of the PR and the rare occurrence and great variability of tropical cyclone structure, intensity, and precipitation amount strongly argues for mission extension to increase sample sizes for statistical analyses.

The PR on TRMM has already provided more data on the vertical structure of precipitation in tropical cyclones than a quarter century of aircraft penetrations into hurricanes in the Atlantic and the Caribbean.[6] The vertical structure information from the PR indicates the distribution of latent heat release in tropical cyclones. This information is used in mesoscale tropical cyclone models. Additionally, PR data are being used to verify the cloud and precipitation structure in such models.[7] Joint Hurricane Testbed projects relate the TRMM data to

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[4]For example, there were several dozen papers at the 26th American Meteorological Society Hurricane Conference on this subject in May 2004.

[5]Frank Marks, NOAA, personal communication, December 2004.

[6]Frank Marks, NOAA, personal communication, November 2004.

[7]Ibid.

several of these models such as those of Geophysical Fluid Dynamics Laboratory, the Eta vertical coordinate model, and the Global Forecast System (Marchok et al., 2004). Further research with TRMM PR data will give a better understanding of the vertical structure of precipitation in tropical cyclones.

In addition to developing mesoscale tropical cyclone models, forecasters are developing models that predict precipitation as a function of the development stage of the storm (from weak tropical depressions on up in intensity to Category 5 hurricanes or Super Typhoons).[8] With improved accuracy of forecast track and storm propagation speed, rain accumulation forecasts have recently become operational based on the published climatology using the early TRMM data (Lonfat et al., 2004). However, the relatively short TRMM record has not sampled a wide variety of extreme events. More hurricane seasons of TRMM data would allow researchers to reduce uncertainty in this forecast tool since more details of the many influences from intensity, location, track speed, and other factors on the rainfall could then be included.[9]

Longer TRMM Record Needed for Climate Research

The value of the relatively short (in climate terms) TRMM dataset for climate research—in particular the interannual to multiyear variability and the interaction of regional with global climate—rises exponentially with every year of added observations.[10] The original motivation for TRMM and its low-Earth, inclined orbit was to collect a benchmark climatology of tropical rainfall averages. This goal has been achieved to a large extent. The more sophisticated climate definition, in terms of the variability of precipitation, requires a longer record to fully characterize and understand the nature of seasonal and interannual precipitation variability. Research using TMI and PR has provided information on the variations in vertical structure of precipitating clouds, the distribution of stratiform and convective rain, diurnal variations in rainfall, and regional and seasonal variability. Even with a seven-year record, the long-term statistics of this variability are not yet well established. Precipitation is an episodic process with small-scale structure, and is therefore much more difficult to characterize than a continuous field such as temperature. The sampling problem becomes particularly severe when attempting to characterize such features as the fine-scale struc-

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[8]Ibid.

[9]For example, research is showing that the often-observed asymmetry of the rainfall between left and right sides of a storm (with respect to the storm's direction of propagation) is related to the wind shear in the lower atmosphere. Forecast wind shear is available from the intensity forecast tool SHIPS, and research to combine this tool with the model R-CLIPER (Rainfall Climate and Persistance) is under way through the Joint Hurricane Testbed.

[10]Testimony of Joanne Simpson, NASA (retired), at the November 8 workshop.

ture of precipitation systems (which requires PR data) and the convective and stratiform structure (Steiner and Houze, 1998). A comprehensive climatology of these features must consider their variability in space by season with type of disturbance and with other factors, which requires that the individual observations be stratified into a number of categories if the results are to be meaningful. Consequently, the existing TRMM database is inadequate for establishing stable and useful statistics for many of these characteristic features of the tropical hydroclimate. Extension of TRMM for a single year would provide important but limited additional sampling and could nonetheless benefit all applications of TRMM data. Even better, an extension to 2010-2011 would almost double the record length and would undoubtedly result in major improvements in the comprehensiveness and robustness of a variety of hydroclimatic statistics, including their year-to-year variability. This extension would become even more valuable if it interfaced with the implementation of the Global Precipitation Measurement mission, thus providing a continuous climate time series beginning in late 1997.

Foster Improving Moist Physics Parameterization for Climate Models, Numerical Weather Prediction, and Related Assimilation Systems by Evaluating Models of Clouds and Precipitation Physics

Global cloud models are advancing and will become a reality in the next 5 to 10 years (Randall et al., 2003; Stephens, 2004). These cloud models will resolve processes on scales that more closely match the native resolution of the TRMM sensors and in a way that more directly links to the observations of TRMM and future satellites like CloudSat (Stephens et al., 2002, 2003). The PR provides an essential source of data for evaluating these cloud process models globally. Spatial and system dependencies mean that longer records are needed, because researchers cannot rely solely on the existing dataset.

ANTICIPATED CONTRIBUTIONS BEYOND THE FUEL POINT (IN ADDITION TO WHAT IS GAINED WHILE CONTROLLED REENTRY IS STILL POSSIBLE)

Anticipated Operational Contributions

Technology Demonstration of First Precipitation Radar in Space

Evaluation of the PR's potential contribution to future radar development, especially with regard to reliability, longevity, and stability, would be enhanced by continuing its operation. Among other things it would help in the design of future spaceborne weather radar technologies in the pipeline.

Operational Assimilation of TMI and PR Data for Weather and Climate Prediction Models

A rapidly increasing number of studies have been demonstrating the value of assimilating passive microwave-retrieved humidity and precipitation information into mesoscale (e.g., Chang et al., 2001; Pu et al., 2002; Kato et al., 2003) and global numerical weather prediction models (e.g., Krishnamurti et al., 2001; Marecal et al., 2002; Aonashi et al., 2004; Hou et al., 2004). Typically, rainfall assimilation has been found to improve the analysis of clouds and radiation fields in areas of active convection, as well as latent heating and large-scale motions in the tropics, while total precipitable water assimilation leads to reduced moisture biases and improved radiative fluxes in clear-sky regions (Hou et al., 2001). A particularly strong case is made by Chang et al. (2001), who demonstrate how assimilation of TMI-retrieved rainfall, integrated water vapor, and sea surface temperature into a mesoscale numerical weather prediction model yielded improved nine-hour forecasts of radar reflectivity cross-sections compared with coincident observations from the PR. The effects of assimilating passive microwave-retrieved rainfall information are especially noticeable for tropical cyclones in terms of their path and intensity, and the kinematic and precipitation structures (e.g., Marecal and Mahfouf 2002; Pu et al., 2002; Hou et al., 2004). Kato et al. (2003) emphasize the importance of the vertical profile of moisture for successfully reproducing the structure and intensity of heavy rainfall over the Kyushu Islands, Japan. Krishnamurti et al. (2001) advocate the value of multi-analysis and multimodel superensembles for achieving higher skills than any of the participating member models.

For reasons of familiarity, spatial coverage, and availability in real time, operational users of TRMM data have focused primarily on TMI and Visible Infrared Scanner observations. Another reason why PR data have not yet been assimilated into numerical weather prediction models is a lack of consistency between the observations and the model physics, which is still largely parameterized particularly in global-scale models. This situation will change as fine-scale, cloud-resolving models are further developed. At present the European Centre for Medium-Range Weather Forecasts (ECMWF) is using PR data primarily as an independent routine validation tool for precipitation analyses (Peter Bauer, personal communication, November 2004; Benedetti et al., 2004a). However, they are exploring the potential value of assimilating PR data into ECMWF's numerical weather prediction model. Initial results with a variational assimilation scheme that adjusts model temperature and specific humidity based on PR reflectivity information, which are subsequently integrated vertically to yield total column water vapor, show a positive effect in the analysis and subsequent forecasts both on moist-related fields and on winds and surface pressure (Benedetti et al., 2004b). Moreover, the forecasted tracks of tropical cyclones more closely match the observations than the tracks obtained by control runs without the above PR-based adjustments. The continued and near-real-time availability of PR data will provide great impetus to move forward with these efforts and those of other groups such as the Joint Center for Satellite Data Assimilation (a NASA, NOAA, and Department of Defense joint center), which plans to focus on the use of cloud and precipitation information. Keeping the TRMM satellite in orbit for as long as possible, therefore, will contribute to the further development of advanced data assimilation schemes that will be needed for the Global Precipitation Measurement era.

Anticipated Research Contributions

Unique Opportunity to Enhance Field Experiment (African Monsoon Multi-Disciplinary Analysis)

If TRMM were extended into at least 2006, it would overlap with and provide valuable input to the African Monsoon Multi-Disciplinary Analysis (AMMA), an international research project with a field campaign scheduled to take place in 2006. The campaign is focused on the eastern North Atlantic Ocean and West Africa. AMMA seeks to better understand the variability of the West African monsoon and to address practical issues related to prediction and applications. As stated in the AMMA research plan, "[s]atellite observations will strongly contribute to the objectives of the project by providing key variables of the surface-atmosphere system (e.g., Meteosat/MSG, ENVISAT, TRMM, AURA, AQUA-Train, TERRA, SMOS . . . [see Appendix J for explanations of abbreviations]). A challenge is to exploit this huge amount of data (20 years for Meteosat, for example) by optimizing the retrievals and data analysis for monitoring as well as validation of models and assimilation. The project will provide a unique set of integrated ground observations for validation of the coming satellites. It will also provide the framework to build a reliable monitoring strategy combining satellite and in situ network, to make up for the low density of routine observations in Africa." Several ships, at least one equipped with a rain radar, are expected to be involved.

AMMA also provides an opportunity for studies of Atlantic tropical cyclone formation, especially on the effect of the Saharan Air Layer (SAL) on cyclone formation. The TRMM data would be helpful for this experiment because of the uniqueness of having the PR co-located with the TMI to reveal the differences in vertical profiles of latent heat release in cases of SAL interaction with the tropical cyclone on the one hand and non-SAL interaction on the other. The TRMM data would help separate physical processes by which the aerosol layer is affecting storm formation and intensification.

Developing the Next Generation of Hurricane Forecast Model

The Joint Hurricane Testbed is a component of the U.S. Weather Research Program that facilitates the transition from research to operations. After years of investment to develop and transition the next generation hurricane forecast model system (called the Hurricane Weather Research and Forecast model), it is scheduled to become operational in 2007. Continuation of the TRMM data streams is needed to enhance the benefits of this effort in terms of improved intensity and precipitation forecasts. For example, the model needs to be validated with high-resolution precipitation data such as PR data. Whereas research aircraft radar can provide some data of similar resolution, a satellite-based system is required to validate the precipitation during all stages in the hurricane life cycle and in regions where research aircraft are not available.

Seamless Transition into the Global Precipitation Measurement Mission

There are obvious merits to achieving this goal, for the many reasons stated in the previous section about extending datasets and, in particular, the cross-calibration value of overlap of TRMM sensors with the Global Precipitation Measurement sensors.

Realization of a Prototype Global Precipitation Measurement-like Operation

The Global Precipitation Measurement mission involves a virtual constellation of satellites served by a "core" satellite. Because of the dimensions of this undertaking, the mission is an across-the-board effort by an international collection of space agencies and partner agencies and organizations. Each member of the constellation is underwritten with its own unique experimental or operational purpose and agenda, but the collective set of platforms produces an integrated global rainfall measurement system. In such constellations the core satellite's orbit is purposefully non-sunsynchronous in order to provide high-quality, diurnal-sampled calibration reference estimates. This assures coincident orbit intersections with all other sunsynchronous and non-sunsynchronous constellation members. Orbit intersections between the core satellite and each of the constellation's remaining members are essential for producing closely coincident data in time needed to determine the systematic biases for the entire set of constellation members. The projected launch year for the core satellite is 2010 at the earliest.[11]

Currently there are two satellites in the constellation—Coriolis and AQUA—and there are planned launches for three other components in the near future:

[11]For up-to-date GPM information, visit the mission Website at http://gpm.gsfc.nasa.gov.

Meteorological Operational Weather Satellite, December 2005 launch; NPOESS Preparatory Project, Fall 2006 launch; and Defense Meteorological Satellite Program, June 2005 launch. Until the core satellite is launched there is an excellent opportunity to prototype several aspects of the Global Precipitation Measurement-era constellation using TRMM as the effective core satellite. If TRMM were extended until the true core satellite launch there would be a seamless transition of radar-calibrated global precipitation measurements into the Global Precipitation Measurement era.

Avoiding Researchers Being Ill Prepared for the Global Precipitation Measurement Mission

The success of TRMM and its unique combination of sensors and special orbit has encouraged development of a cadre of graduate students and researchers now well versed in the intricacies of using a rain radar and a multichannel microwave radiometer in synergy with infrared and visible cloud sensors. If a hiatus of six to eight years in collection of this type of data occurred (between an end of TRMM and the eventual Global Precipitation Measurement mission), training opportunities would be lost. If TRMM continued with near-real-time availability of precipitation data (and with research funding opportunities intact), the community would be ready to take full advantage of the Global Precipitation Measurement constellation.

Better Characterization of Interannual Variability and the El Niño-Southern Oscillation Cycle

Seasonally averaged precipitation in the tropics exhibits pronounced year-to-year variability. The more significant regional-scale variations are associated with large-scale interactions between the atmosphere and land and ocean surface conditions (e.g., soil moisture, sea surface temperature). However, rainfall is not simply a passive response to these interactions. Rather, through the release of latent heat it plays a major role in the dynamics of the interactions. The effects of regional-scale latent heating propagate throughout the tropics and into the extratropics (through teleconnections) where the remote response results in significant climate variability. Consequently a full description and understanding of interannual rainfall variability in the tropics requires both a quantitative description of rainfall anomalies and a diagnostic understanding of the role of rainfall in the coupled processes of the Earth-ocean-atmosphere climate system.

The most extreme and widespread year-to-year variations in tropical rainfall are associated with the ENSO phenomenon. In fact, interannual variability in tropical rainfall is dominated by the ENSO cycle, which arises from coupled ocean-atmosphere interactions in the equatorial Pacific (if above normal sea surface temperature, El Niño conditions result and if below normal sea surface temperature, La Niña conditions). El Niño conditions are associated with massive regional shifts in the precipitation regimes and tropical storm activity, resulting in abnormally heavy rainfall and flooding in normally arid regions and wrenching drought and monsoon failure in other regions. These climate anomalies lead to severe human and socioeconomic effects over large regions of the tropics and affect midlatitude precipitation (e.g., flooding in California during the 1982-1983 and 1997-1998 El Niños).

A meaningful characterization of interannual precipitation variability in the tropics must center on this phenomenon. Climate models have difficulty in realistically simulating the ENSO cycle and its global response. One of several likely reasons for this is an inadequate model representation of the rainfall processes. TRMM provides a reliable quantification of the evolving rainfall field and crucial information on latent heating profiles (only available from the PR). Both are key variables needed for validating the hydrometeorological subcomponents of climate models.

The seven-year TRMM record that now exists includes the later stages of the major 1997-1998 El Niño as well as the weak 2002-2003 event. The differences between these two events illustrate their variability in intensity and character from event to event. While these two realizations are useful for preliminary studies, they are insufficient for a statistical characterization of the hydroclimatic aspects of the ENSO. Since El Niño recurs at irregular integrals of two to seven years, there is a high probability of one or more additional El Niño occurrences between 2005 and 2010. Continuous TRMM observations from 1997 into the Global Precipitation Measurement era would provide a unique and valuable continuous record for the ongoing study and characterization of the ENSO cycle.

CONCLUSIONS

CONCLUSION 4.1: The material in this report provides science and operations information needed as input for a qualitative evaluation of the balance between the risk inherent in an uncontrolled reentry and the contribution through operations and research to the protection of life and property of an extension of the TRMM mission. Extension of the mission to at least late 2005 will provide time for further examination of the relevant issues.

CONCLUSION 4.2: There are persuasive reasons to believe that significant contributions of TRMM to operations and science will continue if the mission is extended. The committee's conclusions about operational and research benefits of extending TRMM either to the fuel point in approximately December 2005 or beyond are compiled in Table 4-1.

CONCLUSION 4.3: From the perspective of anticipated research contributions, TRMM is worth continuing for six primary reasons:

1. TRMM provides a unique complement of measurements. Specifically, the precipitation radar, the passive microwave imager, and the visible and infrared instruments provide a powerful overlap of precipitation, cloud, and water vapor measurements and the lightning imaging sensor helps isolate intense convective cells. In addition, the TMI permits sea surface temperature measurement through clouds at high spatial resolution. Continuation of the mission is vital to the future development of spaceborne precipitation radar technology, especially in the evaluation of the radar technology life cycle.

2. Mission extension creates the opportunity for cross-calibration, validation, and synergy with sensors on future missions, such as CloudSat and the A-Train satellite series, National Polar-orbiting Operational Environmental Satellite System's Conical Scanning Microwave Imager/Sounder, and Global Precipitation Measurement core satellite and other constellation satellites.

3. TRMM's unique low-inclination, low-altitude, precessing orbit enhances science by providing unique spatial and temporal information that fills the gaps in data from other current and upcoming polar-orbiting satellite sensors.

4. TRMM data will enhance field experiments and programs (e.g., TCSP, AMMA, GEWEX, THORPEX, TEXMEX-II), tropical cyclone research (including tropical cyclone forecasting), and development of cloud-resolving models.

5. A longer record is required to collect enough examples to cover the parameter space of synoptic variability more fully. For example, over the first six years of TRMM data, the TMI instrument passes within 750 km of storm centers during one of every eight orbits, whereas PR observes within 250 km of the center during one of every 25 orbits. The narrow swath of the PR and the rare occurrence and great variability of tropical cyclone structure, intensity, and precipitation amount strongly argues for mission extension to increase sample sizes for statistical analyses.

6. Longer TRMM data records will better characterize tropical seasonal-interannual climate variability in general and the ENSO cycle in particular. ENSO is the dominant mode of global interannual climate variability. TRMM provides quantitative ENSO-related tropical rainfall anomalies that are needed to improve our understanding of both the local and remote effects of this phenomenon, and ultimately to make better predictions of its socioeconomic effects in both the tropics and extratropics.

CONCLUSION 4.4: TRMM's reliability combined with the value of TRMM data to operations shows the satellite's potential as an operational system. From a perspective of anticipated operations contributions, TRMM is worth continuing for three primary reasons:

1. TRMM data from the TMI and PR sensors have a demonstrated capability (for TMI) or potential capability (for PR) to improve the weather forecasting process, especially for monitoring and forecasting the tracks and intensity of tropical cyclones and the intensity of rainfall they yield.

2. Continuation of the TMI data stream would enable modelers and forecasters to continue to improve the overall numerical weather prediction process, (i.e., model development and validation, forecast initialization, and forecast verification). This includes use of TMI in calibrating similar data from other microwave sensors and contributes to improved global, as well as tropical, precipitation monitoring and prediction.

3. PR data are an underexploited yet unique resource. Having them available in near real time for an extensive period of time would foster investment of time and effort to make full use of PR data in the forecasting process.

CONCLUSION 4.5: Considering the past and expected scientific and operational contributions presented in this report, important benefits would be obtained if TRMM were extended until it runs out of fuel. Although the scientific and operational arguments by themselves point toward maximum extension of the TRMM satellite life, the committee is concerned that there has not been proper consideration of all three elements of the decision (benefits, costs, and risk). The committee recognizes that consideration of the associated costs and reentry risks has to be part of the decision equation, which requires a solution acceptable to both the user and interagency communities.

RECOMMENDATION

The committee strongly recommends continued operation of TRMM, at least until such time as a decision on controlled reentry becomes unavoidable. The additional year can be used to more fully weigh the benefits, costs, and risks.

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Appendixes

A

Committee Biographies

Eugene 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 particularly 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.

V. Chandrasekar is currently a professor at Colorado State University (CSU). Dr. Chandra has been involved with research and development of weather radar systems for over 20 years and has about 25 years of experience in radar systems. 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 associate director of the newly established National Science Foundation (NSF) Engineering Research Center, Center for Collaborative Adaptive Sensing of the Atmosphere. Dr. Chandra'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. Chandra is co-author of two textbooks, *Polarimetric and Doppler Weather Radar* (Cambridge University Press) and *Probability and Random Processes* (McGraw-Hill). He has authored over 85 journal articles and 150 conference publications and has served as academic advisor 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."

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 to be held 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 AMS, American Geophysical Union (AGU), and the Oceanography Society.

Jeffrey D. Hawkins is the chief 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 will receive 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 January 2003 meeting, and short-course chair for Satellite Precipitation. Mr. Hawkins is an NRC postgraduate advisor, and has served on the NRC Committee on Cooperation with the U.S.S.R. on Ocean Remote Sensing. He has a combined 25 years experience in satellite meteorology and oceanography (sea surface temperature, sea ice, and altimetry).

Kristina Katsaros is a former director of the Atlantic Oceanographic and Meteorological Laboratory, NOAA, 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 an NAE member. Her research interests include processes of momentum, energy, and water transport between sea and air. Dr. Katsaros has used satellite data to estimate the air-sea fluxes, including precipitation, and has attempted to understand the interaction between electromagnetic radiation (visible, infrared, and microwave) with the 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 primarily focused 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 doctor's 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 (SAGE) II and III, co-principal investigator duties for satellite experiment CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite

Observations), and 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. His current research also includes an investigation of the uncertainty of satellite-based rainfall estimates and implications for hydrologic applications. Dr. Steiner just completed two terms on the Committee on Radar Meteorology of the American Meteorological Society. At present he chairs the Technical Committee on Precipitation of the AGU Hydrology Section and is a member of the Precipitation Missions Science Team of NASA and of the Observing Facilities Advisory Panel to the National Science Foundation. He served on the NRC Committee to Assess NEXRAD Flash Flood Forecasting Capabilities at Sulphur Mountain, California. Dr. Steiner is a fellow of the Royal Meteorological Society and was the recipient of the 2002 Editor's Award for the AMS *Journal of Hydrometeorology*.

Graeme 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 principle investigator of NASA's CloudSat Mission. His professional activities include being the editor of a number of leading atmospheric science journals and the 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.

Chris 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 five 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 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 (*Study Director)* is a senior program officer for the Polar Research Board of the National Academies. He directs studies in the areas of polar science and atmospheric science. Before joining the Polar Research Board staff, Dr. Cutler was a senior program officer in the Academies' Board on Earth Sciences and Resources, where he directed the Mapping Science Committee and studies in Earth science and geographic information science. Before joining the Academies, 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.

Leah Probst is a research associate with the NRC's Board on Environmental Studies and Toxicology. She works on a wide variety of studies, including issues such as air quality, climate, ecology, and wildlife management. A former resident of Alaska, Ms. Probst has returned to Alaska many times through her work at the NRC, visiting numerous regions of the state and learning about environmental issues unique to Alaska. She earned her bachelor's degree in biology from the George Washington University in Washington, D.C.

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.

B

Statement of Task[1]

An ad hoc expert committee will be formed to provide advice to the National Aeronatuics and Space Administration (NASA) on the future of the Tropical Rainfall Measuring Mission (TRMM) and potential follow-on research and operational missions. The committee will approach the study in two phases:

PHASE I (THIS REPORT)

The committee will conduct a workshop and prepare an interim report to be delivered in December 2004 on how best to use the remaining TRMM spacecraft life. In particular, the committee and workshop participants will consider:

- Scientific and research contributions of TRMM to date and those expected if TRMM is continued;
- Operational contributions of TRMM to date and those expected if TRMM is continued;
- Assessment of expected benefits of continuing TRMM operation until (1) fuel is depleted to the level needed for a controlled reentry (around December 2005) and (2) until all fuel is depleted (estimated to be 2010-2011).

[1]For an updated version of the Phase II statement of task, see the companion report on GPM (NRC, in review).

PHASE II

The committee will prepare a final report to be delivered in Fall 2005 focusing on needs for satellite-based measurements of tropical rainfall in 2006 and beyond. Specific issues to be addressed include:

- Lessons learned regarding extension of TRMM that would be applicable to other NASA research and development satellites with operational applications and for which extension decisions will be made in the future;
- Any requirement to plan a new follow-on operational satellite that can provide data currently provided by TRMM;
- Optimal use of the Global Precipitation Mission, a spacecraft planned for launch in 2011, which is a research follow-on to TRMM.

C

Workshop Agenda

November 8, 2004
The Keck Center of the National Academies
500 Fifth Street NW
Washington, D.C.

8:00–10:40 Mission Background and Current Context

Welcome—**Gene Rasmusson**, Chair
Current Decision Context at the National Aeronautics and Space Administration (NASA)—**Jack Kaye**, NASA
Mission Beginnings and Evolution—**Joanne Simpson**, NASA
Overview of the Tropical Rainfall Measuring Mission (TRMM) in the Japan Aerospace Exploration Agency (JAXA)—**Hitoshi Tsuruma**, JAXA Washington, D.C., Office
Review of Earlier TRMM Workshop—**Roger Pielke, Jr.**, University of Colorado
Overview of Science, Research, and Operational Performance of TRMM and Plans for GPM (Global Precipitation Measurement)—**Robert Adler**, NASA

11:00–12:30 Tradeoffs and Alternatives—Discussion led by **Gene Rasmusson**, Chair

A What are the data alternatives if TRMM ends in 2004?—**Chris Kummerow**, Colorado State University, and **David Staelin**, Massachusetts Institute of Technology
B What are the trade-offs for continuing the TRMM mission?

1:15–3:15	Future Research and Operational Benefits
	Ed Zipser, University of Utah **Frank Marks**, National Oceanic and Atmospheric Administration (NOAA) **Ken'ichi Okamoto**, Osaka Prefecture University, Japan **Toshio Iguchi**, National Institute of Information and Communications Technology, Japan **Steve Lord**, NOAA **Arthur Hou**, NASA **Jason Ronsse**, Joint Typhoon Warning Center
3:30–4:30	What are the distinctions with respect to TRMM's future value between operating through 2005 versus through ~2010? —Discussion led by **Bob Serafin**, National Center for Atmospheric Research
4:30	Wrap up—**Gene Rasmusson**, Chair
5:00	Adjourn

D

Workshop Participants and Other Contributors

PARTICIPANTS AT THE WORKSHOP

Robert Adler, National Aeronautics and Space Administration
Steve Bilanow, National Aeronautics and Space Administration
Ron Birk, National Aeronautics and Space Administration
Frederick Chen, Massachusetts Institute of Technology
Mary Cleave, National Aeronautics and Space Administration
Gary Davis, National Oceanic and Atmospheric Administration
Gerald Dittberner, National Oceanic and Atmospheric Administration
John Durning, National Aeronautics and Space Administration
David Halpern, Office of Science and Technology Policy
Bob Hamilton, George Mason University
Arthur Hou, National Aeronautics and Space Administration
Toshio Iguchi, National Institute of Information and Communications Technology, Japan
John Janowiak, National Oceanic and Atmospheric Administration
Gregory Jenkins, Pennsylvania State University
Ramesh Kakar, National Aeronautics and Space Administration
Jack Kaye, National Aeronautics and Space Administration
Owen Kelley, National Aeronautics and Space Administration
Chris Kummerow, Colorado State University
Steve Lord, National Oceanic and Atmospheric Administration
Johannes Loschnigg, U.S. House of Representatives Science Committee Professional Staff
Taroh Matsuno, Japan Agency for Marine-Earth Science and Technology

Frank Marks, National Oceanic and Atmospheric Administration
Tetsu Nakazawa, Japan Tropical Rainfall Measuring Mission Science Team
Steven Neeck, National Aeronautics and Space Administration
Andrew Negri, National Aeronautics and Space Administration
Richard Obermann, U.S. House of Representatives Science Committee Professional Staff
Ken'ichi Okamoto, Osaka Prefecture University, Japan
Bill Olsen, National Aeronautics and Space Administration
John Pereira, National Oceanic and Atmospheric Administration
Roger Pielke, Jr., University of Colorado
Amanda Preble, Joint Typhoon Warning Center
Jason Ronsse, Joint Typhoon Warning Center
Kevin Schrab, National Oceanic and Atmospheric Administration
Bob Serafin, National Center for Atmospheric Research
Marshall Shepherd, National Aeronautics and Space Administration
Joanne Simpson, National Aeronautics and Space Administration (retired)
Bob Simpson, National Oceanic and Atmospheric Administration (retired)
Eric Smith, National Aeronautics and Space Administration
David Staelin, Massachusetts Institute of Technology
Hitoshi Tsuruma, Japan Aerospace Exploration Agency
Greg Williams, National Aeronautics and Space Administration
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E

Letter from World Climate Research Programme/WMO to Administrator O'Keefe (NASA) and Dr. Yamanouchi (JAXA), July 6, 2004

Dr. Sean O'Keefe
Administrator
NASA Headquarters
300 E Street SW
Washington, DC 20546
USA

Dr. S. Yamanouchi
President
Japan Aerospace Exploration Agency
World Trade Center Building
2-4-1 Hamamatsu-Cho, Minato-ku
Tokyo 105-8060
Japan

6 July 2004

Dear Dr. O'Keefe and Dr. Yamanouchi,

In our capacity as Chairman and Vice-Chairman of the Joint Scientific Committee for the World Climate Research Programme (WCRP), we would like to relay the deep concern of our scientific community regarding the possibility of the premature loss of the TRMM (Tropical Rainfall Measurement Mission) satellite. Because of both its dramatic scientific contributions (which would increase significantly as the data record increases) and its use in operational forecasting of hazardous weather, we urge you to maintain TRMM's operational capability for as long as feasible. This issue has been raised by many of our colleagues worldwide who certainly feel that the continuation of TRMM is critical to the development and success of several key projects in climate research. TRMM's unique orbit and instrumentation (including the only rain radar in space) make its information impossible to replace with other forms of data currently available. We understand that the satellite and instrumentation are in excellent condition. It would seem, therefore, that the operational cost of maintaining the satellite would be a small fraction of the original investment, and certainly worthwhile. Furthermore, TRMM is a key research element for the development of the Global Earth Observation System of Systems advocated both by the US and Japanese governments, and its early termination would seem to go against the very objectives of this initiative.

The main aim of WCRP is to develop the fundamental scientific understanding of the physical climate system and climate processes, as needed to determine to what extent climate can be predicted and the extent of human influence on climate. As an international coordinating body for climate research, WCRP represents a large community of scientific users of Earth Observation satellite data and has developed a strong working relationship with space agencies in order to foster the use of their products and contribute to the definition of missions relevant to its objectives. TRMM is a critical satellite in the monitoring and study of our planet's water cycle and climate, and thus central to WCRP's interests.

WCRP is an associated member of CEOS and is actively involved in the international GEO (Group on Earth Observations) initiative. WCRP's position on space mission requirements for climate research has been recently updated by an international working group, which expressed its deep concern that the TRMM operation might be terminated prematurely. Indeed, it recommended that, "TRMM operations be continued for as long as possible in order to collect the longest possible and unique precipitation dataset over the tropical regions for climate study (and also in preparation for later GPM / Megha Tropiques missions). The group also felt that the benefit for society, including saving of life and property by improved forecasts of extreme meteorological events that could result from continued operation of TRMM, should be put in balance with the risk to life and property related to an uncontrolled re-entry."

TRMM observations have contributed significantly to the WCRP Global Water and Energy Cycle Experiment (GEWEX), including the on-going CEOP (Coordinated Enhanced Observing Period) project, which represents a pilot global experiment to observe the various components of the global water cycle. We would also like to stress the important contribution of TRMM to other WCRP core projects, especially the Climate Variability and Predictability (CLIVAR) study where TRMM data are being used in studies of the monsoons, hurricane forecasting, precipitation over Africa and sea-surface-temperatures. WCRP is presently proposing a new strategic framework for its activities under the acronym COPES (Coordinated Observation and Prediction of the Earth System) in which satellite-derived precipitation measurements will represent a key element. The role of TRMM data will be essential in this undertaking.

In view of the above, various messages of support for TRMM continuation have already been sent to your agencies by the Director of WCRP, the Chairman of GEWEX, and many others in the WCRP scientific community. However, in view of the importance of the matter and the urgency of the situation for a large scientific community relying on your programmes, we felt compelled to personally send this letter to you at the highest management level. On behalf of WCRP, we would highly appreciate any option NASA and JAXA may consider to maintain the TRMM operation as long as reasonably feasible.

We thank you in advance for any action you can take on this matter.

Yours sincerely,

Peter Lemke
Chair, JSC for the WCRP

John Church
Vice-Chair, JSC for the WCRP

cc: Dr G. Asrar, NASA
Dr Y. Furuhama, JAXA
Dr D.J. Carson, WCRP

F

Letter from Rep. Boehlert to Dr. Marburger, July 22, 2004

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE

July 22, 2004

The Honorable Dr. John H. Marburger, III
Director
Office of Science and Technology Policy
Executive Office of the President
Washington, DC 20502

Dear Dr. Marburger,

I'm writing to urge you to intervene in a decision the National Aeronautics and Space Administration (NASA) has made to de-orbit the Tropical Rainfall Measuring Mission (TRMM) satellite. As I'm sure you're aware, TRMM is a tremendously successful satellite program. As a research satellite, it has provided unprecedented insights into the nature of precipitation and contributed significantly to our understanding of the hydrological cycle, the effects of storms on the Earth's radiation budget, and global climate. It has also dramatically improved our ability to track hurricanes. Near real-time data from the satellite are routinely being used by the National Oceanic and Atmospheric Administration (NOAA) and the Department of Defense in their tropical cyclone models.

Although the satellite is technically capable of continuing to serve both science and the nation, NASA has said that it is unable to find the funding to continue flying TRMM. According to NASA, the Japan Aerospace Exploration Agency, NASA's partner developing TRMM, has declined to contribute additional funding, and so has NOAA.

But we urge you to work with NASA, NOAA, the Department of Defense, and any other agency that benefits from the data TRMM provides to find the additional funding to keep the satellite in service. The cost of keeping the satellite functional is minuscule compared to the value it provides.

Further, we believe this case unfortunately is only the most recent example of a longstanding problem regarding the transition of research satellites that NASA builds and launches into working satellites that other agencies, such as NOAA, might operate. More attention must be devoted to how to better coordinate satellite operations between agencies, so as to prevent currently operational and valuable resources like TRMM from being wasted.

I look forward to working with you to ensure the continuance of the TRMM mission and to rectifying the broader problem of identifying and maintaining the valuable capabilities of research satellites in an operational capacity.

With Best Regards,
Sincerely,

SHERWOOD L. BOEHLERT
Chairman

cc: Sean O'Keefe, Administrator, National Aeronautics and
Space Administration
V ADM (Ret.) Conrad C. Lautenbacher, Administrator,
National Oceanic and Atmospheric Administration

G

Letter from Rep. Lampson to President Bush, July 23, 2004

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE

July 23, 2004

The President
The White House
Washington, DC 20500

Dear Mr. President:

I am writing to express my concern over NASA's announcement that it intends to terminate the Tropical Rainfall Measuring Mission (TRMM) later this year. I believe that such a step is ill-advised and will increase the risk to life and property from hurricanes, typhoons, and other severe storms over the next two years. As you know, such storms have devastated Texas and many other parts of the United States on numerous occasions over the last half-century. I urge you to take whatever steps are necessary to preserve this unique space-based capability so that it may continue to support hurricane forecast operations for as long as possible.

TRMM has been one of NASA's most successful Earth science missions, exceeding both its estimated operational lifetime and its performance specifications. The spacecraft and its sensors continue to operate flawlessly, and there is no indication that its systems are in danger of degrading any time soon.

The data produced by TRMM have *"given unprecedented insights into rainfall producing cloud systems over tropical land masses and oceans,"* according to NASA. In addition, TRMM has proven to be an invaluable resource to weather forecasting agencies around the world in improving hurricane and typhoon tracking. In the United States, both the National Hurricane Center and the U.S. Navy's Joint Typhoon Warning Center use TRMM to reduce risk to lives and property from hurricanes and typhoons.

The primary objection to operating TRMM for an additional two years appears to be financial rather than safety-related. However, your Administration should be able to find a few tens of millions of dollars over the next four years to preserve a key means of improving coastal and maritime safety. A viable funding arrangement can certainly be developed between NASA and the other agencies that use TRMM's data if you desire it to happen.

I hope that you will intervene to help protect our citizens from the increased risk that would result from a termination of TRMM's operations this year.

Sincerely,

NICK LAMPSON
Ranking Democratic Member
Subcommittee on Space and Aeronautics

H

Letter from Vice Admiral Lautenbacher to Administrator O'Keefe, July 23, 2004

United States Department of Commerce
The Under Secretary of Commerce
for Oceans and Atmosphere
Washington, D.C. 20230

JUL 23 2004
The Honorable Sean O'Keefe
Administrator, National Aeronautics
and Space Administration
Two Independence Square
300 E Street, S.W.
Washington, D.C. 20546

Dear Sean,

I am writing to document the National Oceanic and Atmospheric Administration (NOAA) and other users concerns about the recent decision by the National Aeronautics and Space Administration (NASA) to terminate the Tropical Rainfall Mapping Mission (TRMM).

TRMM data has had a positive impact on NOAA's numerical weather prediction models, improving the forecast accuracies for hurricanes, tropical storms, and other tropical weather disturbances affecting the United States and its possessions. Given that we are in the active phase of the typhoon season in the east Pacific and are entering the active phase of the Atlantic hurricane season, I am requesting we explore a way to continue the operation of TRMM through the end of this year's hurricane season, November 30, 2004.

In addition, the highly successful NOAA/NASA partnership has led NOAA to implement QUIKSCAT data in our operational models, and begin assimilating AIRS and MODIS data into operational models by the end of the year, another major success for the NASA/NOAA Joint Center for Satellite Data Assimilation (JCSDA). Given our growing dependence on these NASA satellite instruments, I would appreciate an opportunity to work with you to develop a more formal mechanism for dialogue with NASA well in advance of any termination date for research data streams.

I believe such a joint consultative process would also help to support the growing leadership role of the United States in the Global Earth Observing System of Systems. Making the maximum use of research and operational satellite data, as well as joint planning for transitioning successful research instruments to operational status, will demonstrate a sustained commitment to advancing earth sciences.

If you concur, I recommend for your consideration that Greg Withee, NOAA Assistant Administrator for Satellites and Information Services, dialog with Ghassem Asrar and Al Diaz, in order to find a more effective way, perhaps through a joint working group, to explore such research to operations issues as TRMM, and to recommend solutions. I look forward to enhancing the great value the NOAA/NASA partnership brings to science and the American public. With great appreciation and respect for the strong working relationship that has developed between NOAA and NASA under your leadership!

Sincerely,

Conrad C. Lautenbacher, Jr.
Vice Admiral, U.S. Navy (Ret.)
Under Secretary of Commerce for
Oceans and Atmosphere

I

Letter from Administrator O'Keefe to Vice Admiral Lautenbacher, August 3, 2004

National Aeronautics and
Space Administration
Office of the Administrator
Washington, DC 20546-0001

August 3, 2004

The Honorable Conrad C. Lautenbacher
Under Secretary of Commerce
for Oceans and Atmosphere and
NOAA Administrator
Department of Commerce
Washington, DC 20230

Dear Admiral Lautenbacher:

Thank you for your letter of July 23, 2004, regarding the National Oceanic and Atmospheric Administration's (NOAA) interest in continued operation and use of the Tropical Rainfall Measuring Mission (TRMM) spacecraft. Since the launch of TRMM, NASA has worked closely with NOAA to optimize the use of TRMM to provide experimental research data to NASA, while also providing unique and timely operational data to NOAA. Our Japanese space agency partner, JAXA, has also been an integral part of this joint research and operational collaboration. The result has been an unprecedented international cooperation that has benefited people around the world.

Following the completion of TRMM's mission objectives in 2000, NASA, NOAA and JAXA have extended the life of TRMM for over 3 years to continue receipt of this valuable stream of data. NASA engineers have used a number of unique spacecraft operations techniques to extend TRMM in an orbit that has provided valuable data to NOAA. As TRMM approaches the limits of its operational life, we have welcomed the opportunity to work with NOAA to obtain all possible data from TRMM, while also planning for a safe, controlled deorbit of the spacecraft. Our options for safe reentry become increasingly limited the longer we operate TRMM, as it is already more than 3 years beyond design life.

NASA is glad to continue working with NOAA and JAXA to further extend TRMM operational life, in light of NOAA's renewed interest in continued receipt of TRMM data through 2004. We have an experienced NASA-NOAA-JAXA operational team that can determine methods necessary to obtain all possible data from TRMM, while also planning for a safe, controlled deorbit of the spacecraft. I have directed our team to proceed expeditiously on this work with NOAA and JAXA. As an immediate step our TRMM team will, consistent with good engineering practices, maintain TRMM in an operational, data collection status as these discussions move forward.

Based upon our shared interest, I have taken the liberty of requesting that the National Academy of Sciences (NAS) hold a workshop in September 2004 to advise NASA and NOAA on:

- Best use of remaining TRMM spacecraft life;
- Safe, controlled deorbit of TRMM;
- Advisability of transfer of operational responsibility for TRMM to NOAA for the remainder of mission life;
- Any requirement for a follow-on operational satellite that can provide data currently provided by TRMM; and,
- Optimal use of the Global Precipitation Mission, a spacecraft planned for launch in 2011 that is a research follow-on to TRMM.

In the next few months, it would also be useful to open a dialogue with the NAS on the wisest way to use experimental research data in operational models, both nationally and internationally. This would allow a comprehensive consideration of worldwide Earth science research data and its applicability to operational uses such as disaster warning, and predictive capabilities in areas such as weather and agriculture. As part of this dialogue, the NAS could share new ideas on how to approach the phasing of NASA research spacecraft capabilities into varied NOAA operational uses.

In addition, I thoroughly agree with your assessment that NASA and NOAA should work in concert with other Departments and Agencies to develop more formal mechanisms to maximize use of research and operational satellite data and to plan for transition of successful research instruments to operational status.

This type of long-range planning is critical to our Agencies' ability to optimize use of our unique Earth remote sensing capabilities to benefit all Americans. Further, such efforts will enhance our Nation's leadership role in the Global Earth Observing System of Systems, fostering our work with countries around the world in a sustained commitment to advancing Earth sciences for the benefit of humankind.

I look forward to our continued work on this issue and the enhancement of the strong partnership between NASA and NOAA in advancing science of importance to our Nation.

Cordially,

Sean O'Keefe, Administrator

J

Abbreviations

4-DVAR	Four Dimensional Variational Data-Assimilation system
AGU	American Geophysical Union
AIRS	Advanced Infrared Sounder
AMMA	African Multi-Disciplinary Monsoon Analysis
AMS	American Meteorological Society
AMSR-E	Advanced Microwave Scanning Radiometer for EOS (Earth Observing System)
AQUA	satellite of NASA's Earth Observing System (EOS)
A-Train	AQUA-Train
AURA	satellite of NASA's Earth Observing System
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMEX	Convection and Moisture Experiment
CEOP	Coordinated Enhanced Observing Period
CEOS	Committee on Earth Observations Satellites
CERES	Clouds and Earth Radiant Energy System
CHILL	National Radar Facility at Colorado State University
CLIVAR	Climate Variability and Predictability Research
CloudSat	Cloud Satellite
CMIS	Conical scanning Microwave Imager/Sounder
COARE	Coupled Ocean-Atmosphere Response Experiment
COPES	Coordinated Observation and Prediction of the Earth System
CSU	Colorado State University

DMSP	Defense Meteorological Satellite Program
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
ENVISAT	Environmental Satellite
EOS	Earth Observing System
FNMOC	Fleet Numerical Meteorology and Oceanography Center
FY-3	Fengyun-3
GCOM	Global Change Observing Mission
GEO	Group on Earth Observations
GEWEX	Global Energy and Water Cycle Experiment
GHz	gigahertz
GOES	Geostationary Operational Environmental Satellites
GPM	Global Precipitation Measurement
GSFC	Goddard Space Flight Center
IPWG	International Precipitation Working Group
JAXA	Japan Aerospace Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JMA	Japan Meteorological Agency
JSC	Joint Scientific Committee
JTWC	Joint Typhoon Warning Center
km	kilometer
lidar	light detection and ranging
LIS	Lightning Imaging Sensor (on TRMM)
MADRAS	Microwave Analysis & Detection of Rain & Atmosphere Structure
Meteosat	Meteorological Satellite
MODIS	Moderate Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
MWRI	Microwave Radiation Imager
NAE	National Academy of Engineering
NASA	National Aeronautics and Space Administration
NCEP	National Centers of Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service

NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRC	National Research Council
NSF	National Science Foundation
OSTP	Office of Science and Technology Policy
OTA	Office of Technology Assessment
PR	Precipitation Radar
QUIKSCAT	Quick Scatterometer
R-CLIPER	Rainfall CLImate and PERsistence
SHIPS	Statistical Hurricane Intensity Prediction Scheme
SIGMET	significant meteorological advisory
SMOS	Surface Meteorological Observation System
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager/Sounder
SST	sea surface temperature
TC	tropical cyclone
TCSP	Tropical Cloud Systems and Processes
TERRA	NASA's Earth Observing System (EOS) flagship satellite
TEXMEX	Tropical Experiment in Mexico
THORPEX	The Observing-System Research and Predictability Experiment
TMI	TRMM Microwave Imager
TOGA	Tropical Oceans and Global Atmosphere Programme
TRaP	Tropical Rainfall Potential
TRMM	Tropical Rainfall Measuring Mission
VIRS	Visible and Infrared Scanner
WCRP	World Climate Research Program
WindSat	Wind Satellite
WMO	World Meteorological Organization

K

Examples of Improvements in Tropical Cyclone Nowcasting Gained from TRMM

INTRODUCTION

Many tropical cyclones hide their true center location under a central dense overcast that obscures the eye and/or eyewall from detection in visible and infrared images. Consequently, storm location estimates from visible and infrared imagery can be off up to 200 km when clouds mask the true storm center. Poor position estimates typically occur during a storm's formative stages and when the low-level center is not aligned with the central dense overcast's expansive cloud shield. Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) data can reveal the storm center by enabling the analyst to find the eye or banding eye features that otherwise would not be visible.

Microwave imagers other than TMI have the same general capability, but only TMI and AMSR-E currently have the 5-km 85 GHz resolution and frequency attributes. TMI's unique orbit allows it to temporally sample storms when no polar orbiters can, thus filling a data void. In addition, the 35-degree orbital inclination permits TMI data to sample storms during consecutive orbits (for example, three or four orbits for storms approaching Japan). Frequent views provide the continuity to understand the link between storm structure evolution and intensity changes.

The National Hurricane Center and the Joint Typhoon Warning Center routinely incorporate TRMM data to monitor tropical cyclones within their warning areas. This is also the case at the Air Force Weather Agency, NOAA's Satellite Analysis Branch (Camp Springs, Maryland) and the Tropical Satellite Analysis Branch (Miami, Florida). In 2004, these centers created more than 600 tropical cyclone fixes using TMI data (Table K-1). Because of the high spatial resolution

TABLE K-1 Tropical Cyclone Center Fixes in 2004 (up to December 9)

Location	Number of Fixes
Southern Hemisphere	202
Western Pacific Ocean	296
Atlantic Ocean	58
East Pacific Ocean	88
Indian Ocean	25
Total	669

NOTE: The number of fixes is a function of (1) the number of tropical cyclones within each basin, (2) frequency of TMI overpasses while a storm is alive, and (3) diligence of satellite fixing agencies in gathering TMI data in near real time for fixes.

of TMI data (5 km at 85 GHz), these fixes are typically assigned very high quality when compared with all other satellite location datasets (e.g., visible, infrared, and microwave sensors such as SSM/I and AMSU-B). Thus, the TMI fixes drive both the near-real-time warning positions and typically the best track created when all data is compiled after a storm has completed its life.

The National Hurricane Center and the Joint Typhoon Warning Center include TMI in their storm discussions that outline how the data have affected their warning positions or provided insight on storm structure that directly influences storm intensity estimates and/or short-term intensity trends. This appendix provides examples of how TMI data are used for intensity estimates and fixing storm locations.

SPECIFIC IMPACTS OF TRMM DATA

Tropical Cyclone Maximum Intensity: Kenna

"Now that Kenna [Figure K-1] *has developed a vertically deep eye feature in the TRMM data and the center is embedded in the middle of the CDO* [Central Dense Overcast] . . . *a 24-hour period of rapid intensification is being forecast."* (From Tropical Storm Kenna Discussion Number 6 at 2 am PDT October 23, 2002.)

Impact of TRMM data: TRMM data led the Tropical Prediction Center to correctly change its forecast from "intensification" to "rapid intensification."

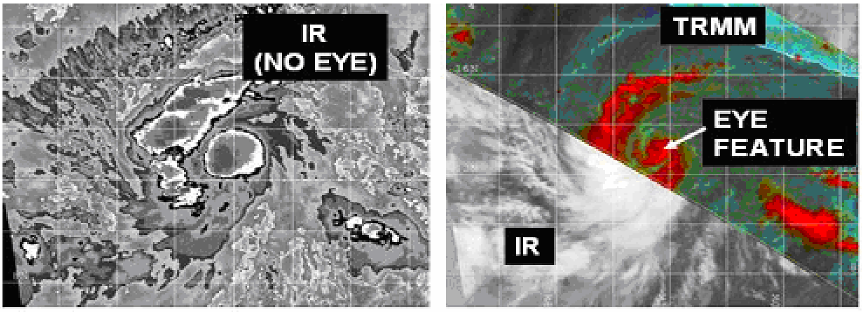

FIGURE K-1 Comparison of TRMM TMI data with GOES Infrared Data Showing the improved ability to detect the eye of Tropical Cyclone Kenna. IR = infrared. SOURCE: Naval Research Laboratory Tropical Cyclone Web Page Team.

Tropical Cyclone Maximum Intensity: Dalila

"A TRMM satellite overpass at 1205Z . . . showed only a partial eyewall at best . . . which casts some doubts as to whether Dalila was as strong as previously thought. The maximum winds are decreased to 65 kts for this advisory . . ." (From Hurricane Dalila Discussion Number 16 at 2 pm PDT July 24, 2001.)

Impact of TRMM Data: The Tropical Prediction Center decreased its estimate of the maximum winds by 5 knots and correctly changed its intensity forecast from "strengthening" to "weakening."

Tropical Cyclone Position/Track: Felicia

"The cloud pattern is not well organized and the low-level center is very difficult to find on IR [Infrared] *images. A 1259Z TRMM pass shows the low level center to the north and well removed from the convection."* (From Tropical Storm Felicia Discussion Number at 8 am PDT July 19, 2003.)

Impact of TRMM data: The data enabled the Tropical Prediction Center to position the center properly.

Tropical Cyclone Size and Structure: Genevieve

"The latest TRMM pass at 0055 UTC indicates Genevieve may not be vertically aligned with different center fixes from the 85 GHz and 37 GHz channels. Thus the initial intensity is held at 60 knots for this advisory." (From Tropical Storm Genevieve Discussion Number 9 at 8 pm August 27, 2002.)

Impact of TRMM data: NOAA conventional satellite estimates indicated Genevieve was a hurricane with 65 knot winds. TRMM data allowed the Tropical Prediction Center to correctly assess that Genevieve was instead a tropical storm with 60 knot winds. Genevieve never became a hurricane.

Tropical Cyclone Formation and Type: Subtropical Depression 12

"On the other hand . . . a TRMM overpass at 1601Z indicated that the maximum winds were at least 100 n mi [nautical miles] *from the center . . . which is rather unlike a tropical cyclone. The low is thus upgraded to a subtropical depression instead of a tropical depression."* (From Subtropical Depression Twelve Discussion Number 1 at 5 pm EDT September 20, 2002.)

Impact of TRMM data: The Tropical Prediction Center used TRMM data to properly classify the system a subtropical depression rather than a tropical depression. This distinction is important to users because subtropical systems usually develop less rapidly than tropical systems. This system remained subtropical and developed slowly for the following two days.

Fixing the Center of a Hurricane: Hurricane Kyle

"*The first images after the eclipse period were not helpful in determining a center fix for Kyle. However a 0657 UTC TRMM pass provided the additional detail for an accurate fix at synoptic time. The TRMM data also indicates a system that is still vertically aligned."* (From Hurricane Kyle discussion number 31, National Weather Service, Miami, Florida, 5 am EDT, September 28, 2002.)

Impact of TRMM data: First accurate fix of the center of the hurricane.

Advanced Warning of Storm Intensity: Typhoon Vamei

"*The TRMM pass triggered the rapid warning on this system with the USS Carl Vinson Battle Group just departing Singapore. With the advance warning they were able to strategize and safely route through the system. The TRMM pass also validated its intensity. Without it, we probably would have warned, but lower (45 knots) based on QUIKSCAT. That's probably the best example we've had to date*." (Source: Joint Typhoon Warning Center.[1])

FURTHER EXAMPLES OF TROPICAL CYCLONE DISCUSSIONS THAT ILLUSTRATE OPERATIONAL USE OF TRMM DATA

Tropical Storm Danny Discussion Number 4

NWS TPC/NATIONAL HURRICANE CENTER MIAMI, FL, 5 AM EDT, JULY 17, 2003

[1]See https://www.npmoc.navy.mil/jtwc/atcr/2001atcr/ch1/chap1_page39.html.

"DANNY CONTINUES TO BECOME BETTER ORGANIZED AS INDICATED BY IMPROVED BANDING FEATURES AND A 17/0339Z **TRMM** OVERPASS INDICATING A 10 NMI DIAMETER EYE-LIKE FEATURE . . ."

Tropical Storm Blanca Discussion Number 14

NWS TPC/NATIONAL HURRICANE CENTER MIAMI, FL, 2 AM PDT, JUNE 20, 2003

"AFTER BEING DEVOID OF THUNDERSTORM ACTIVITY FOR THE PAST SEVERAL HOURS . . . NEW PATCHES OF DEEP CONVECTION HAVE RE-DEVELOPED NEAR THE CENTER. DVORAK T-NUMBERS SUGGEST THAT BLANCA IS BARELY A TROPICAL STORM BUT BECAUSE THERE WAS THERE WAS AN EXTREMELY WELL-DEFINED CENTER ON THE 0347Z **TRMM** PASSAGE . . . THE INITIAL INTENSITY IS KEPT AT 35 KNOTS AT THIS TIME . . . "

Tropical Storm Enrique Discussion Number 9

NWS TPC/NATIONAL HURRICANE CENTER MIAMI, FL, 8 AM PDT JULY 12, 2003

"ENRIQUE MAINTAINS AN IMPRESSIVE CONVECTIVE PATTERN . . . WITH CLOUD TOPS TO -80C NEAR THE CENTER. HOWEVER . . . A **TRMM** OVERPASS AT 0802Z SHOWED NO EYE AND A PARTLY EXPOSED LOW-LEVEL CENTER WEST OF MAIN CONVECTIVE BANDS…"

Tropical Storm Felicia Discussion Number 7

NWS TPC/NATIONAL HURRICANE CENTER MIAMI, FL, 8 AM PDT, JULY 19, 2003

"THE CLOUD PATTERN IS NOT WELL ORGANIZED AND THE LOW-LEVEL CENTER IS VERY DIFFICULT TO FIND ON IR IMAGES. A 1259Z **TRMM** PASS SHOWS THE LOW LEVEL CENTER TO THE NORTH AND WELL REMOVED FROM THE CONVECTION. A SLIGHT STRAIGHTENING IS POSSIBLE BEFORE WEAKENING OVER COOL WATERS BEGINS IN ABOUT 36 HOURS . . . "

Hurricane Ignacio Discussion Number 11

NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL, 8 AM PDT, AUG 24, 2003

"IGNACIO HAS CONTINUED TO STRENGTHEN . . . WITH A SMALL EYE EMBEDDED IN VERY COLD-TOPPED CONVECTION . . . ALTHOUGH RECENT ENHANCED IR IMAGES SHOW SOME WARMING OF THE CLOUD TOPS. **TRMM** DATA SHOWED A 10 N MI DIAMETER EYE WITH A WELL-DEFINED EYEWALL . . . AND FIRST-LIGHT VISUAL PICTURES SHOW A CLOUD-FILLED EYE . . . "

Hurricane Ignacio Discussion Number 12

NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL, 2 PM PDT, AUG 24, 2003

"THE INTENSIFICATION EVENT NOTED EARLIER TODAY HAS ENDED. **TRMM** AND SSM/I IMAGERY SUGGEST THAT IGNACIO HAS GONE THROUGH AN EYEWALL REPLACEMENT . . . WHICH COULD EXPLAIN THE RECENT LEVELING OFF IN INTENSITY . . . "

Hurricane Jimena Discussion Number 6

NWS TPC/NATIONAL HURRICANE CENTER MIAMI FL, 8 AM PDT AUG 29, 2003

"ENHANCED INFRARED AND MICROWAVE IMAGERY DEPICT THAT JIMENA CONTINUES TO INTENSIFY. DVORAK INTENSITY ESTIMATES ARE 77 KT FROM TAFB . . . 65 KT FROM SAB . . . 55 KT FROM CPHC AND 55 KT FROM AFWA. A 0923Z **TRMM** PASS REVEALED A DISTINCT . . . SMALL EYE BENEATH THE DEEP CONVECTION. BASED ON THIS DATA . . . THE TROPICAL STORM IS UPGRADED TO HURRICANE JIMENA WITH 65 KT SUSTAINED WINDS . . . "

Hurricane Jimena Discussion Number 15

NWS CENTRAL PACIFIC HURRICANE CENTER HONOLULU HI, 5 AM HST, AUG 31, 2003

"HURRICANE JIMENA INTENSITY REMAINS AT 90 KNOTS WITH DVORAK SATELLITE INTENSITIES OF 4.5 FROM PHFO AND SAB [Satellite Anaysis Branch] . . . AND 5.0 FROM JTWC. INITIAL MOTION IS

270/15 KT. BOTH INTENSITY AND MOVEMENT REMAIN UNCHANGED FROM 6 AND 12 HOURS AGO.

UW-CIMSS VERTICAL WIND SHEAR ANALYSIS INDICATES THAT JIMENA CONTINUES TO ENCOUNTER A SOUTH SOUTHWESTERLY SHEAR OF ABOUT 12 KNOTS. OUTFLOW ALOFT IS IMPEDED ON THE WESTERN SIDE OF JIMENA BECAUSE OF THE SHEAR. A **TRMM** PASS AT 0907Z CENTERING JIMENA AT 17.9N 146.4W SHOWED THAT THE EYEWALL WAS OPEN ON THE SOUTH SIDE. THIS INDICATES THAT THE SYSTEM IS IN A WEAKENING PHASE . . . PROBABLY BECAUSE OF THE VERTICAL WIND SHEAR AND THE RELATIVELY COOL SEA SURFACE TEMPERATURES OVER WHICH JIMENA IS PASSING . . . ”

Tropical Depression Eleven-E Discussion Number 5

NWS TPC/NATIONAL HURRICANE CENTER MIAMI, FL, 8 AM PDT SEP 04, 2003

“LATEST SATELLITE IMAGERY AND MICROWAVE DATA FROM A 12Z **TRMM** PASS INDICATE THE CENTER OF TROPICAL DEPRESSION ELEVEN-E IS ABOUT A DEGREE TO THE NORTH OF THE PREVIOUS ADVISORY POSITION. FURTHER RE-LOCATION MAY BE NECESSARY ONCE MORE VISIBLE IMAGES BECOME AVAILABLE. THE DEPRESSION REMAINS A BROAD CIRCULATION AND SATELLITE INTENSITY ESTIMATES FROM BOTH TAFB AND SAB ARE 30 KNOTS. THE INITIAL INTENSITY WILL REMAIN AT 30 KNOTS . . . ”

Tropical Depression Kevin Discussion Number 8

NWS TPC/NATIONAL HURRICANE CENTER MIAMI, FL, 2 AM PDT, SEP 05, 2003

“TROPICAL DEPRESSION KEVIN HAS BECOME A FULLY EXPOSED LOW-LEVEL CIRCULATION. ENHANCED INFRARED SATELLITE IMAGERY AND A 0436Z **TRMM** PASS DEPICT THAT THE CENTER IS DISPLACED APPROXIMATELY 90 MILES NORTH OF THE DEEP CONVECTION . . . ”

Hurricane Marty Discussion Number 13

NWS TPC/NATIONAL HURRICANE CENTER MIAMI, FL, 8 PM PDT, SEP 21, 2003

"MARTY HAS BECOME MUCH BETTER ORGANIZED DURING THE PAST 6 HOURS. DEEP CONVECTION HAS RE-DEVELOPED OVER THE LOW-LEVEL CENTER AND A RAGGED CLOUD-FILLED EYE HAS BRIEFLY APPEARED IN BOTH VISIBLE AND INFRARED SATELLITE IMAGERY. HOWEVER . . . A 21/1926Z **TRMM** OVERPASS SHOWED A WELL-DEFINED LOW- TO MID-LEVEL EYE . . . SUGGESTING THAT THE INNER-CORE WIND FIELD REMAINED WELL ORGANIZED DRUING THE EARLIER WEAKENING PHASE . . . "