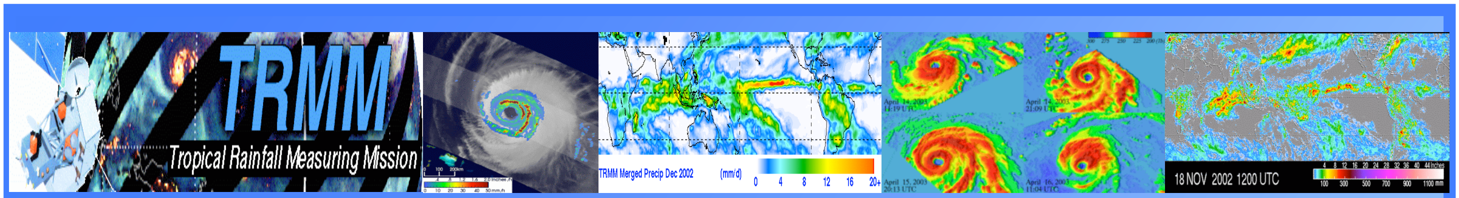
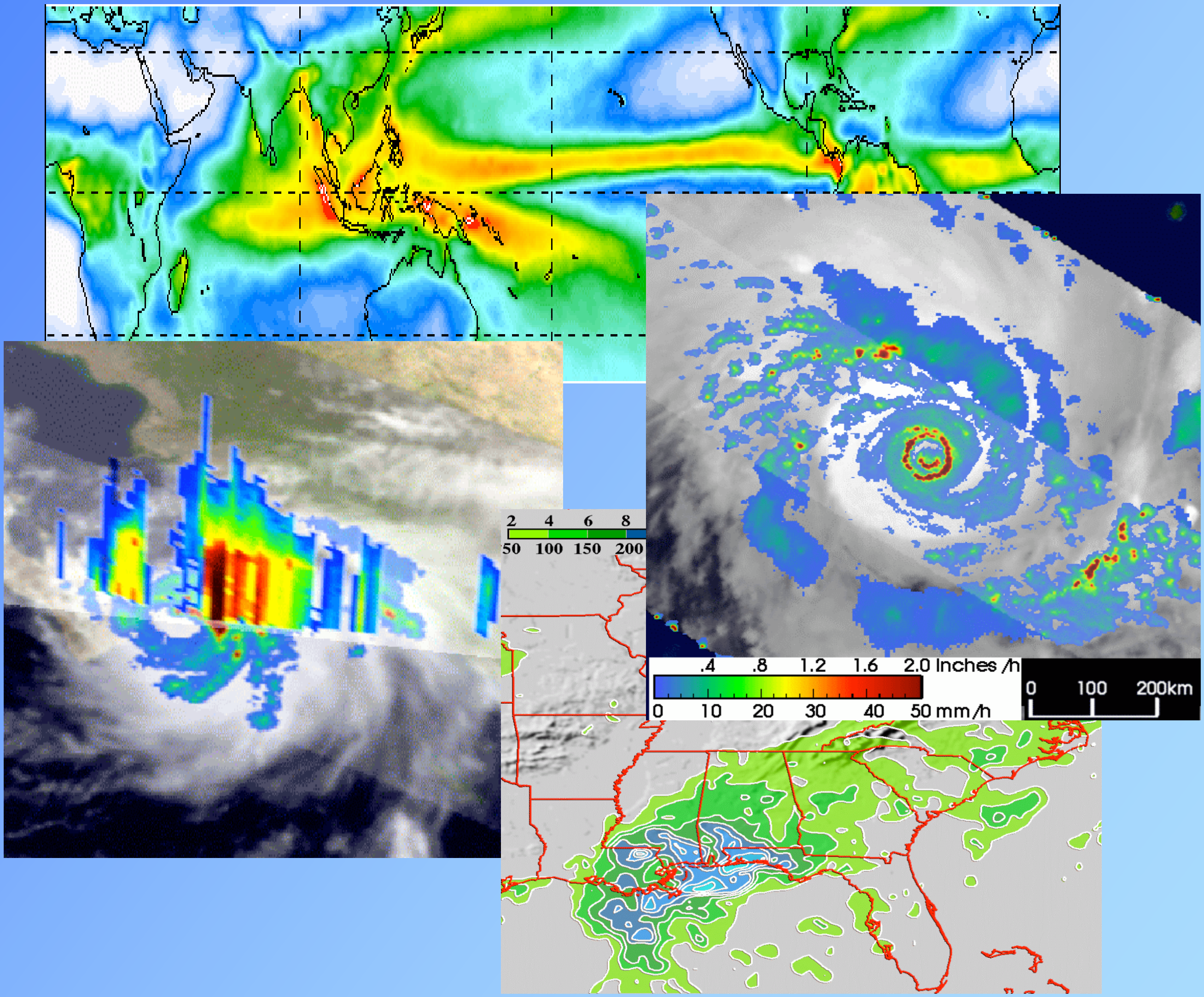


Tropical Rainfall Measuring Mission

TRMM

Senior Review Proposal

2007



National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, MD 20771

March 15, 2007

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TO: NASA Headquarters
Attn: Acting Associate Administrator for Science Mission Directorate

FROM: 100/Director

SUBJECT: Tropical Rainfall Measuring Mission (TRMM) Senior Review Proposal

Enclosed is the 2007 TRMM Senior Review proposal in response to NASA's request. We are very excited about the continuation of the TRMM mission.

The first-time use of both active and passive microwave instruments and the precessing, low inclination orbit (35 degrees) have made TRMM *the world's foremost satellite for the study of precipitation and associated storms and climate processes in the tropics*. TRMM has met and exceeded its original goal of advancing our understanding of the distribution of tropical rainfall and its relation to the global water/energy cycles and weather. Extension of TRMM will allow for continuation of critical water cycle and climate research, operational use of TRMM data for monitoring tropical cyclones and other hazardous weather, and aid significantly in preparation for the Global Precipitation Measurement (GPM) mission to be launched in 2013. The TRMM satellite and its instruments are in excellent shape and there is sufficient station-keeping fuel on board to maintain science operations until 2012-2013. TRMM flight operation and data processing costs have been significantly reduced for the extension period. TRMM data processing is shifting to the Precipitation Processing System, being developed as part of NASA's Precipitation Program to process TRMM, GPM, and other relevant satellite precipitation data. A multi-year extension of TRMM has a very high payoff for science and applications, but at a low additional cost to NASA.

In conclusion, I assure that the scientific, engineering, management, facility, and other support that is necessary for the on-time and within budget of delivery of the TRMM extension will be available and committed to the TRMM program. With this understanding, I fully endorse this proposal.

Edward J. Weiler

Edward J. Weiler

Enclosure

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TRMM Senior Review Proposal
Executive Summary

The Tropical Rainfall Measuring Mission (TRMM), launched in late 1997, is a joint mission between NASA and JAXA, the Japanese space agency. **The first-time use of both active and passive microwave instruments and the precessing, low inclination orbit (35°) have made TRMM *the world's foremost satellite for the study of precipitation and associated storms and climate processes in the tropics*.** TRMM has met and exceeded its original goal of advancing our understanding of the distribution of tropical rainfall and its relation to the global water and energy cycles. TRMM has evolved from an experimental mission focusing on tropical rainfall climatology into the primary satellite in a system of research and operational satellites used for analyzing precipitation characteristics on time scales from 3-hr to inter-annually and beyond. Continuation of TRMM data will allow the community to better link the TRMM data set to that of the Global Precipitation Measurement (GPM) mission to be launched in 2013.

The overall science objective of an extended TRMM mission is *to determine the time and space varying characteristics of tropical rainfall, convective systems, and storms and how these characteristics are related to variations in the global water and energy cycles.* This TRMM goal is at the heart of NASA's Earth Science strategy and the answering of key science questions for both the Water and Energy Cycle and Weather focus areas, i.e., *"How are global precipitation, evaporation and the water cycle changing?"* and "*How can weather forecast duration and reliability be improved?* Having a long, accurate record of quasi-global precipitation characteristics is critical to achieving NASA Earth Science goals. The TRMM satellite and the associated science program will provide that data and science to NASA and the world research community. The **National Academy** has already spoken on this subject. In a recent independent assessment of the benefits of extending TRMM, they clearly stated that **"*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.*" (NRC, 2006).**

Significant scientific accomplishments have already come from TRMM data, including reducing the uncertainty of mean tropical oceanic rainfall; a documentation of regional, diurnal, and inter-annual variations in precipitation characteristics; the first estimated profiles of latent heating from satellite data; improved climate simulations; increased knowledge of characteristics of convective systems and tropical cyclones; and new insight into the impact of humans on rainfall distributions. The availability of real-time TRMM data has led to significant applications and operational use of TRMM data, primarily in the monitoring of tropical cyclones, in hydrological applications and in assimilation of precipitation information into numerical forecast models.

Extension of TRMM will result in: *1) an improved climatology of precipitation characteristics, especially extremes; 2) improved diagnosis and closure of global (and regional) water cycles; 3) diagnosis and testing of inter-decadal and trend-related processes in the water cycle; 4) assessment of the impact of humans (e.g., cities, deforestation, and aerosols) on rainfall characteristics and processes; 5) robust determination of convective system, tropical cyclone, and lightning characteristics; 6) advances in hydrological applications over land (basin-scale assessments, water management); 7) improved modeling of the global water/energy cycles for weather/climate predictions; and 8) improved monitoring and forecasting of tropical cyclones, floods and other hazardous weather.*

The TRMM satellite and its instruments are in excellent shape and there is sufficient station-keeping fuel on board to maintain science operations until 2012-2013. TRMM flight operation and data processing costs have been significantly reduced for the extension period. TRMM data processing is shifting to the Precipitation Processing System (PPS), being developed as part of NASA's Precipitation Program to process TRMM, GPM and other relevant satellite precipitation data. The basic mission continuation will continue production of TRMM standard and real-time products, while additional research products will be added as part of an enhanced mission. ***A multi-year extension of TRMM has a very high payoff for science and applications, but at a low additional cost to NASA.***

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TRMM Deputy Project Scientist: Scott Braun
TRMM Science and Data Information System (TSDIS) Manager: Erich Stocker
TRMM Mission Director: Julio Marius

Precipitation Measurement Missions (PMM) Science Team

Basic Mission Continuation Section

1. TRMM MISSION BACKGROUND, ORGANIZATION, AND STATUS

1.1 Introduction

The Tropical Rainfall Measuring Mission (TRMM) is a joint project between NASA and the Japanese space agency, JAXA. It was launched on November 27, 1997 and continues to provide the research and operational communities unique precipitation information from space well into 2007. The first-time use of both active and passive microwave instruments and the precessing, low inclination orbit (35°) make TRMM the world's foremost satellite for the study of precipitation and associated storms and climate processes in the tropics. Complete information about the TRMM mission can be found at the U.S. TRMM web site http://trmm.gsfc.nasa.gov.

The overarching TRMM science goal is to advance our knowledge of the global energy and water cycles by observing time and space distributions of tropical rainfall, convective systems and storms, and their associated hydrometeor structure and latent heating distributions. TRMM has met and exceeded this research goal and is a major observational success of NASA's Water and Energy Cycle and Weather research programs over the last decade. Continuation of TRMM is critical to the future success of NASA's water and energy cycle research through exploitation of TRMM's extended data set, which with each additional year becomes increasingly valuable for climate variability and climate change studies. Extension of TRMM also provides the potential of a cross-calibration overlap with the Global Precipitation Measurement (GPM) mission (or at least only a small gap), providing the possibility of an unprecedented observational record of accurate precipitation with which to probe climate variability and change within the water cycle from 1997 to 2015 and beyond.

The primary TRMM instruments are the *Precipitation Radar (PR)*, the first and only rain radar in space, and the *TRMM Microwave Imager (TMI)*, a multi-channel passive microwave radiometer, which complements the PR by providing total hydrometeor (liquid and ice) content within precipitating systems. The *Visible Infrared Scanner (VIRS)* is used to provide the cloud context of the precipitation structures and is used as part of a transfer strategy to connect microwave precipitation information to infrared-based precipitation estimates from geosynchronous satellites. These three instruments form the original TRMM rain package and are used singly and jointly to understand precipitation processes, structure and climatology. In addition, the *Lightning Imaging Sensor (LIS)*, an EOS-funded instrument, has complemented the rain sensors and improved understanding of convective dynamics and provided a climatology of global lightning flash rates. The CERES Earth radiation budget instrument on TRMM failed after eight months of flight and is not addressed here. Table 1 summarizes the characteristics of the TRMM rain instruments and Fig. 1 shows the swath geometry of the various instruments. Additional information on the TRMM instruments is given in Section 1.5.

1.2 History—Development, launch, boost

The TRMM concept was developed in the 1980's, driven by a scientific need for climatological precipitation information to understand the global water cycle and for investigation of atmospheric convective systems, cyclonic storms and precipitation processes. The first of a series of TRMM workshops was held in late 1986, with results described in a report (Simpson, 1988) and journal article (Simpson et al. 1988). During the 1980's, discussions and joint work between U.S. and Japanese scientists in the development and use of an experimental aircraft precipitation radar evolved toward interest in a joint satellite project.

The TRMM satellite was built in-house at Goddard with the instruments delivered from manufacturers (including the PR from Japan). The assembled satellite was then shipped by aircraft to Japan where it was successfully launched from JAXA's Tanegashima launch site on an H-II rocket on November 27, 1997. The *TRMM orbit altitude originally was 350 km* and the inclination is 35°, so that the satellite covered the tropics and the southern portions of both Japan and the United States. The precessing orbit also passes through all the hours of the day, thereby giving a unique data set for observing the diurnal cycle of rainfall. The first full month of data was January 1998. Although the CERES instrument failed after eight months, all the precipitation

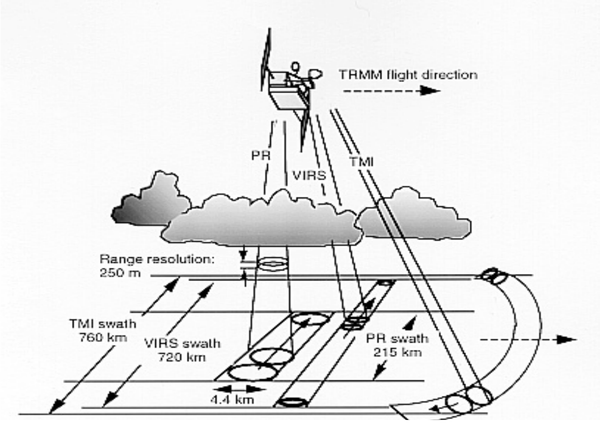

Fig. 1. Schematic of TRMM satellite and scanning geometries of three rain package instruments.

Table 1. TRMM Sensor Summary – Rain package

Microwave radiometer (TMI)	Radar (PR)	Visible and infrared Radiometer (VIRS)
10.7, 19.3, 21.3, 37.0, and 85.5 GHz (dual-polarized except for 21.3: vertical only)	13.8 GHz	0.63, 1.61, 3.75, 10.8, and 12 µm
11 km X 8 km field of view at 37 GHz	5-km footprint and 250-m vertical resolution	2.5-km resolution
Conically scanning (53^0 inc.)	Cross-track scanning	Cross-track scanning
880-km swath	250-km swath	830-km swath

package instruments (PR, TMI, VIRS) and the LIS have functioned perfectly for over nine years.

TRMM was originally designed to provide data for a minimum of three years, with a goal of five years. Because of its low altitude (necessary for high signal for the radar and for fine spatial resolution of highly variable rain fields), TRMM has a small propulsion system used to maintain near-constant altitude against the effect of atmospheric drag. Although launched with over 800 kg of fuel for the propulsion system, by early 2001 (three years into the mission), TRMM scientists faced an early end of the mission in 2002 or 2003 due to lack of fuel. *After careful analysis of the benefits and drawbacks, the TRMM science teams (U.S. and Japan) proposed increasing the orbit altitude by about 50 km in order to decrease atmospheric drag and extend mission life.* After extensive review, NASA and JAXA agreed to the mission extension plan and ordered the boost to the higher altitude. *The boost to 402.5 km (+/- 1.0 km) was carried out in August 2001* and TRMM has operated at that altitude since that date. The exact altitude chosen (402.5 km) is related to the pulse repetition frequency (PRF) of the PR. TRMM has now operated at the higher 400-km altitude for a longer period (~ 5.5 years) than at the earlier, lower 350-km altitude (~ 3.7 years).

Although TRMM started as an experimental mission to study tropical rainfall, and was originally expected to last only 3-5 years, it has evolved into the primary satellite in a system of research and operational satellites monitoring precipitation on time scales from 3-hr to inter-annually and beyond. TRMM's role as the primary satellite in this system is because of the high quality precipitation information available from its active-passive combination of instruments and the inclined orbit visiting the entire diurnal cycle with frequent intersections with polar-orbiting satellites. Today TRMM data are used to calibrate and integrate precipitation information from multiple polar orbiting satellites/instruments (AMSR on Aqua, SSM/Is on DoD/DMSP and AMSU on NOAA platforms) and geosynchronous satellites into merged precipitation analyses being used both for research and applications. The real-time availability of TRMM products has also resulted in the use of TRMM data by operational weather agencies in the U.S. and around the world for monitoring and forecasting of tropical cyclones, floods and other hazardous weather.

1.3 TRMM spacecraft operations

The TRMM spacecraft is currently operated by Capitol College personnel under the direction and management of the Earth Science Mission Operations (ESMO) Project at Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. The Flight Operations team is responsible for planning, monitoring the health and safety of the spacecraft, coordinating science and data recovery, and mission management activities. All real-time operations are performed utilizing the Space Network (SN), which consist of the Tracking and Data Relay Satellite System (TDRSS) and the user scheduling system at White Sands Complex (WSC), New Mexico. Normally operations personnel schedule sixteen-to-eighteen SN events to meet mission operations requirements. These requirements include: the planning of all daily activities, on board recording management and data recovery, generation and uplink of daily command loads, special operations loads necessary for orbit adjust (delta-V) maneuvers and yaw maneuvers, and special request for real time commands. It should be noted that TRMM virtual recorders (VR) must be dumped approximately every 2.5-hours to avoid the VR's going into overflow mode that will cause no new data to be recorded.

The TRMM Operations Control Center (OCC) located at GSFC is presently staffed eighteen hours per day, seven days a week (18x7), with one on-call engineer on duty at all times in the event of any operational problem. During this lights-out mode of operations from midnight to 6:00 AM daily, three to four health and safety contacts with TRMM are performed along with science data dumps. Command modifications have been incorporated and are now included as part of the daily command load to the onboard C&DH system. This has been possible due to the ground system re-engineering effort by ESMO to introduce automation into flight operations activities. As a result, Flight Operations personnel have been operating in this "lights-out" mode of operation during the midnight shift since April 2006. Lights-out operations capitalize on existing automation of the operational ground system, the inherent onboard spacecraft capabilities and the SN/WSGT support reliability. The success of the automation is reflected in the high data capture rate during calendar year 2006. The overall data capture rate for the TRMM mission was 99.94% and for the operational instruments is as follows:

PR:	2006 data capture 99.95%
VIRS:	2006 data capture 99.95%
TMI:	2006 data capture 99.96%

The automation effort and other cost saving strategies have resulted in a significant decrease in flight operations costs since the earlier portion of the mission.

The LIS is technically an EOS instrument flying on TRMM. Marshall (MSFC) is the responsible facility with data capture of 99.90% for the LIS.

1.4 TRMM spacecraft status

The TRMM spacecraft is in excellent shape after nine years in orbit. An independent technical assessment of extended life of the TRMM spacecraft was performed by the Mission Engineering and Systems Analysis Division (Code 590) of Goddard in 2004. The assessment was led by John Deily, the Associate Chief of the Division. In particular, the following are noted from the presentation report:

- Redundancy Assessment:
  No credible single point failures;
  All credible faults have block or functional redundancy
- Probability of TRMM's life being limited by radiation or Atomic Oxygen effects through 2010 – *very low;*
- Probability of TRMM's life being limited by reaction wheel failures through 2010 – *very low*;
- Probability of TRMM's life being limited by gyro failures through 2010 – *very low.*
- Probability of critical hardware failure vs. time:
  24 month failure probability <4%;

Since this study, there have been no significant changes to any spacecraft systems, so that the results of the study still hold.

The most serious spacecraft problem affecting TRMM was with the Solar Array Drive Actuators (SADA). The two solar arrays are designed to track the sun. One array, the –Y side array, is always on the sun, or warm, side (TRMM does routine yaw maneuvers to keep one spacecraft side toward the sun). The –Y side SADA has operated at environmental temperatures beyond design limits since launch. In 2002, the –Y SADA briefly malfunctioned (did not fail) and it was decided to park the array (discontinue sun tracking) in the horizontal position to avoid the possibility of that array becoming stuck in a non-preferred position. This lack of sun tracking with the one solar array has led to slightly less available power, but still allows sufficient power for nominal operations of all working instruments (CERES was powered down at this point). The +Y drive is operating well within temperature limits and is not expected to experience the same problems. However, because of the situation with the –Y side solar array, the power subsystem requires special attention during state of charge (SOC) periods, especially during periods of low Beta angle (seasonally varying satellite-sun angle). The SOC is carried out by real-time commanding of the Voltage-Temperature level during low Beta angle periods.

In summary, in terms of TRMM mission extension impacting spacecraft systems, the *"change in risk is minimal."* (Deily presentation).

1.5 Description and status of TRMM instruments

Precipitation Radar (PR). **The PR is the first rain radar in space and will be the only rain radar in space until GPM**. Its key observation goals can be summarized as 1) providing three-dimensional structure of rainfall, particularly the vertical distribution and 2) obtaining high quality, quantitative rainfall measurements over land as well as over ocean. The PR was developed by the Japanese National Institute of Information and Communication Technology (NICT) and JAXA. It is a 128-element active phased array system operating at 13.8 GHz. The transmitter/receiver (T/R) consists of 128 solid-state power amplifiers and PIN-diode phase shifters. The T/R element is connected to a 2-m slotted waveguide antenna, by which a 2 m × 2 m planar array is constructed. The PR uses a frequency agility technique to obtain 64 (N_s = 64) independent samples with a fixed PRF of 2776 Hz. The PR antenna scans in the cross-track direction over ±17° (215-km swath). The PR performs an external calibration with a ground-based Active Radar Calibrator (ARC) about four times a year and an internal loop calibration to measure the transfer function of the PR receiver about once a day.

The TRMM PR has operated perfectly over the lifetime of the satellite. Instrument calibration has been very steady, with absolute accuracy of less than +/-0.5 dB and long-term relative stability of 0.1 dB. The PR calibration is so steady it has been used as a calibration standard for ground radars. Recently, Kojima (2005) reviewed the reliability of the PR with regard to the mission extension. The report states that the PR has no moving parts (electrically scanning) affecting instrument lifetime and found that heatpipe and mechanical thermostat components also did not limit mission extension. Total radiation dose for an extended mission is within limits. None of the 128 array elements have failed during the mission and the PR can operate with up to four failures. **Therefore, because there is no known component limiting its life, the PR is projected as highly probable to continue operating nominally for the next five years.**

TRMM Microwave Imager (TMI). The **TMI is a nine-channel passive microwave radiometer based upon the Special Sensor Microwave/Imager (SSM/I)**, which has been flying aboard the U.S. Defense Meteorological Satellite Program (DMSP) satellites since 1987. The key difference is the addition of a pair of 10.7 GHz channels with horizontal and vertical polarizations, which allowed for the first microwave-based SST measurements. The TMI antenna is an offset parabola, with an aperture size of 61 cm (projected along the propagation direction) and a focal length of 50.8 cm. The antenna beam views the earth surface with an incident angle of 52.8° at the earth's surface. The TMI antenna rotates about a nadir axis at a constant speed of 31.6 rpm. The rotation draws a "circle" on the earth's surface.

The TMI has operated perfectly since TRMM launch. TMI calibration has been steady with no drift or deterioration. Because of its heritage from the SSM/I instruments, TMI lifetime can be projected from SSM/I performance. Of the six SSM/I's launched, three are still operating with lifetimes so far of 14, 12 and 9 years. Three other SSM/I's were operating at 7, 9 and 17 years when the spacecraft failed in one case and was turned off in the other cases. **Thus, there is a high probability that the TMI will operate successfully for five years or more.**

Visible and InfraRed Scanner (VIRS). **The VIRS is a five-channel imaging spectroradiometer with bands in the wavelength range from 0.6 to 12 µm.** The VIRS data are used to obtain cloud information using visible and IR techniques in order to provide a cloud context to the microwave-based precipitation retrievals, and also a link to rain estimation techniques and products derived from visible/infrared geosynchronous satellite data. The VIRS has the same center wavelengths and bandwidths as the Advanced Very High Resolution Radiometer (AVHRR) that has flown since 1978 on the National Oceanic and Atmospheric Administration (NOAA) series of spacecraft. The major differences between the two systems are the 2.1-km nadir IFOV for VIRS in contrast to 1.1 km for the AVHRR and the fact that the VIRS has an onboard solar diffuser for post launch calibration of the two reflected solar bands.

The TRMM/VIRS sensor continues to provide reflected solar and thermal emissive radiometry from five spectral bands with nadir spatial resolution of 2 kilometers. Performance has been excellent with exceptional stability in the thermal emissive bands. **Long term trending has revealed only minor response degradations and there is every indication that the VIRS should continue to operate as designed for the foreseeable future.** The non-sun-synchronous TRMM orbit in combination with VIRS's exceptional stability has resulted in the unanticipated use of VIRS as a transfer standard for comparing the radiometric accuracy of imaging radiometers such as Terra and Aqua MODIS, AVHRR, and AIRS.

Lightning Imaging Sensor (LIS). **The LIS detects all ("total") lightning, since cloud-to-ground, intracloud, and cloud-to-cloud discharges all produce optical pulses that are visible from space.** The LIS consists of an optical staring imager, with a sampling rate slightly greater than 500 frames per second, which identifies lightning activity by detecting momentary changes in the brightness of the clouds as they are illuminated by lightning discharges. Due to the sensitivity and dynamic range of the sensor, it can detect lightning during daytime even in the presence of bright, sunlit clouds. A wide field of view lens, combined with a narrow-band (10 A) interference filter, centered on a strong optical emission multiplet (OI (1) at 777.4 nm), is focused on a small, high speed 128 × 128 element CCD array. The 80 deg × 80 deg angle field of view, combined with the 400 km altitude, permit the sensor to view clouds within a 600 km × 600 km area of the Earth with a spatial resolution of 3 km (at nadir) for almost 90 sec as TRMM passes overhead. The LIS data products are produced, archived, and reprocessed at and distributed from the Global Hydrology and Climate Center in Huntsville, AL (http://thunder.msfc.nasa.gov).

The LIS continues to provide full functionality. Long term instrument trending indicates that performance continues to be exceptional. **The LIS has no moving parts and because there is no known component limiting its life, it is projected as highly probable to continue operating nominally for the next five years**.

1.6 The TRMM Science Data and Information System

The TRMM Science Data and Information System (TSDIS) is the data processing system for TRMM, producing all the PR, TMI and VIRS, combined instrument and multi-satellite standard products. It produces up to 12 GB/day of initial science data from the satellite. TSDIS gets the L0 (raw data with effects of telemetry removed) from the Sensor Data Processing Facility (SDPF). It uses the L0 data to generate the starting level 1 processing L1A (instrument counts reversible to L0). TSDIS personnel interact with the science team algorithm developers (including those in Japan) of L2 and L3 products to incorporate them into the processing stream, ensure that they produce the expected output and provide trending information for analysis. All standard science products are sent to the GSFC Distributed Active Archive Center (DAAC) for the distribution to the general public and for user support for this group. TSDIS also has responsibility for reprocessing TRMM data. The reprocessing requirement is to provide an additional 2X (24 GB additional) satellite data reprocessing. The Version 6 re-processing of the standard products was completed in 2005. Planning for a Version 7 reprocessing in 2008 is underway. In addition, TSDIS produces real-time versions of most of the Level 2 products and the real-time multi-satellite analysis (TRMM Multi-satellite Precipitation Analysis [TMPA], product designation: 3B-42RT). In addition to the standard products provided to the wider community, TSDIS also provides the opportunity for science team members to run more specific algorithms on the TRMM data, thus greatly reducing the data infrastructure required by individual PIs. TSDIS, as part of the overall NASA Precipitation Program is evolving into the Precipitation Processing System (PPS) as we move toward GPM. **Current computer hardware is gradually being replaced during TRMM mission operations, with later additional modifications accomplished with GPM project funding.**

1.7 Ground validation data processing

A key component of the TRMM project is the Ground Validation (GV) effort (http://trmm-fc.gsfc.nasa.gov/trmm_gv). **The GV effort is primarily a data collection and product generation program. Ground-based radar and raingauge data are collected and quality-controlled, and validation products are produced for comparison with TRMM satellite products.** Detailed information and product analysis is available on the TRMM GV web site. The four primary GV sites are Darwin, Australia; Houston, Texas; Kwajalein, Republic of the Marshall Islands; and, Melbourne, Florida (Wolff et al 2005). The list of GV products is given in Appendix A.

The largest part of the validation effort involves the routine, careful collection, processing and product generation of ground-based radar, rain gauge and disdrometer data in order to produce standard validation products. Products are produced using techniques developed to produce carefully quality-controlled ground radar data sets and estimated surface rainfall rates, adjusted by quality-controlled rain gauge data. The procedures for performing these tasks are optimized to take advantage of each site's strengths. The primary radar data quality control (QC) algorithm masks non-precipitation echoes by use of adjustable echo-height and reflectivity thresholds. Additional QC algorithms make use of signal quality and semi-permanent ground clutter sources (Silberstein et al. 2007). Rain gauge data QC is performed on several automated levels, one of which is a procedure to filter unreliable rain gauge data upon comparison to radar data (Amitai 2000). To ensure GV data products are of the highest possible quality, dependent and independent rain gauge data (when available) are compared with radar estimates via scatter-plot analysis. Further analyses include time series comparisons of gauge and radar rain rates and detailed study of QC results. These efforts have resulted in standard validation data sets, at both instantaneous and monthly time scales, with which to compare TRMM-based rain estimates, and have helped to establish the accuracy of the various TRMM products. In addition, other specific gauge data sets are used to produce additional validation products. GV products have been used extensively by many groups for validation research and published in peer-reviewed journals (Liao et al. 2001; Habib and Krajewski 2002; Datta et al. 2003; Houze et al. 2004; Gebremiachael and Krajewski 2004; Huffman et al. 2006; Wolff and Fisher 2007).

Because of the highly variable nature of precipitation, it is important to have high quality validation data and a diverse variety of cases from different climate regimes and covering different time periods. The number of regional GV sites is limited due to the need for high quality data and the logistical demands of producing the validation products. Therefore, it is very important for the validation products to cover various seasons and inter-annual variations to provide the natural variability in precipitation amounts and other characteristics with which to test the satellite estimates. **For these reasons, the TRMM program continues to produce validation products and should continue to do so in the future as the validation effort evolves into the broader validation program of GPM.**

1.8 TRMM end-of-life plan

TRMM's propulsion system is used to maintain its relatively low orbit (400 km) against drag. Currently, orbit maneuvers are performed about once a month using about 1.2 kg of fuel each time. As of March 1, 2007, TRMM is estimated to have 122 kg of fuel remaining. Based only on station-keeping fuel availability, *TRMM has the potential to stay on station doing science until 2012-2013*. TRMM is operating under a Mission Extension Plan developed to operate the satellite until the fuel has been depleted and the satellite is more than five km below the International Space Station.

The TRMM End-of-Life (EOL) Plan has specific assigned trigger levels in the event of a single anomaly or multiple component failures. If there is an onboard anomaly or failure which precludes science data collection, the science mission may be terminated early. Any fuel remaining will be depleted and the orbit lowered to the maximum extent possible prior to depleting the other energetic sources and terminating mission operations in compliance with NASA Policy Directive 8710.3B, "NASA Policy for Limiting Orbital Debris Generation" and Orbital Debris Mitigation under NSS 1740.14. The ESMO Project intends to update the TRMM EOL Plan periodically depending on the status of the spacecraft. Specifically, the TRMM EOL plan delineates the specific activities required to safely decommission the spacecraft in accordance with NASA policy by:

1) Minimizing the potential for generation of orbital debris due to explosion or collision by venting all remaining hydrazine. This will require a series of planned burns.
2) Passivation of the spacecraft by cessation of battery charging and active attitude control.
3) Turning off the on-board subsystems in a systematic manner to minimize impact on final shut-off of the spacecraft.
4) Deactivation of communications subsystems to preclude the ability of the spacecraft to act as an RF source.

The TRMM EOL Plan provides for both an emergency and an orderly termination of the mission. The plan also includes the lessons learned during the successful decommissioning of the ERBS in October 2005 and UARS in December of 2005 by the ESMO Project.

2. SUMMARY OF TRMM ACCOMPLISHMENTS TO DATE

TRMM's enormous success is related to its two unique attributes that make it ideal for observing tropical rainfall systems: (1) its suite of *complementary observing instruments* and (2) its *orbit characteristics*. TRMM provides a complementary suite of active and passive sensors flown on a single platform, providing the most complete view of precipitation. Due to its complement of instruments, TRMM has been called the "flying rain gauge", i.e., **the space standard for precipitation observation**. The TRMM observing system employs the only precipitation radar in space, the PR, which 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 the passive microwave TMI are only now reaching the point where TRMM's potential to act as a global rainfall reference standard is being utilized. **Without the PR in space, there will be no similar opportunity for calibration with an active sensor until GPM is launched in 2013**.

TRMM's unique orbital characteristics enable it to fill temporal and spatial sampling gaps from all current and soon-to-be-launched microwave satellite sensors. TRMM's 35-degree inclination, low altitude (402.5 km), and non-sun-synchronous orbit provide multiple benefits when compared with the space and time sampling dictated by standard polar orbiting 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.

One measure of TRMM's contribution is the large number of refereed publications that mention TRMM (Fig. 2). The TRMM launch triggered a virtual flood of research that has led to significant improvements in our understanding of the hydrologic cycle, of the climate system, and of tropical weather systems and their prediction. **The total of TRMM-related research papers now numbers well over 700**. The complete list can be found at http://trmm.gsfc.nasa.gov.

TRMM products are used extensively by the research and applications communities as indicated by usage statistics from the Goddard DISC. For the annual average over the life of TRMM, the total volume of data distributed was 6.7 times greater than the volume ingested into the archive. Adjusted to remove greater than usual volumes ingested due to reprocessing, the ratio of distribution to ingest becomes greater than 9 to 1. Level 3 products during the life of the mission enjoy an annual average volume distribution of 25.9 times greater than the volume ingested. **These data-use ratios for TRMM are some of the highest of data sets residing at the Goddard DISC**. In addition, since launch, the number of users requesting TRMM data has gone up every year, as the significance of TRMM data

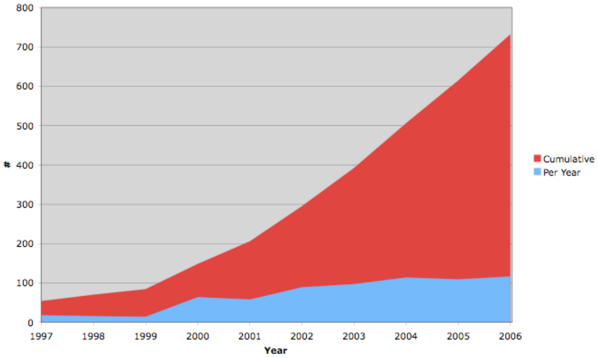

Fig. 2. Publication data show the yearly and cumulative totals and are obtained by searching the Institute for Scientific Information's Science Citation Index for papers that mention TRMM either in the title, abstract, or keywords.

was realized by scientists and, more recently, by applications researchers.

A summary of TRMM's scientific contributions in various categories, with an emphasis on findings from the past two years, is given in the following sub-sections. Selected papers have been highlighted in Table 2. TRMM's original science goals have been met and many additional contributions have been made, beyond what was originally expected.

2.1 Climate-related research

Rainfall climatology. TRMM's new knowledge on rain distribution across the tropics has lead to **a benchmark nine-year rain climatology (Fig. 3), narrowing considerably the range of uncertainty in previous space-based rainfall estimates (Adler et al. 2003; Nesbitt et al. 2004)**, and to the unique monitoring of rainfall variations related to ENSO (Masunaga et al 2005; L'Ecuyer et al 2006). The TRMM surface rainfall retrievals from the multiple instruments and algorithms are converging to become the standard for improving long-term climatologies and for comparison with climate models.

Diurnal cycle. TRMM has allowed the **heretofore-impossible quantification of the diurnal cycle of precipitation and convective intensity over land and ocean tropics-wide (e.g., Nesbitt and Zipser 2003; Bowman et al. 2005) through the use of the PR.** While early studies focused on the diurnal cycle on global scales, the continued accumulation of data has allowed for a focus on the diurnal cycle at regional scales, including South America (Hong et al. 2006a), the Maritime Continent (Ichikawa and Yasunari 2006; Zhou and Wang 2006), and the Himalayas (Bhatt and Nakamura 2006).

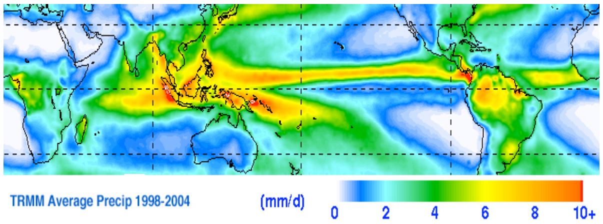

Fig. 3. Nine-year climatology of surface precipitation from TRMM Version 6 3B-43 multi-satellite product combined with gauge information.

Convective/stratiform climatology. The radar aboard the TRMM satellite has allowed **tropics-wide mapping of rainfall separated into its two main types, convective and stratiform, for the first time.** This separation largely determines the vertical structure of latent heating associated with tropical precipitating systems and the corresponding large-scale atmospheric response (Schumacher et al. 2004). It also varies regionally, seasonally, and by type of system (Morita et al. 2006, Schumacher and Houze 2006).

Lightning climatology. The use of the lightning sensor, LIS, in conjunction with rain information has lead to a **detailed global mapping of lightning distribution, quantifying the lightning/convection relation for land and ocean** (Petersen et al. 2005, 2006; Takayabu 2006). On a global scale, the relationship between precipitation ice water path and lightning flash density is relatively invariant between land, ocean, and coastal regions (Petersen et al. 2005). Over the southern Amazon, the lightning frequency and vertical structure of convection are modulated by the phase of the monsoon (Petersen et al. 2006), with the southerly phase characterized by an increase in lightning flash density, mean ice water path, and a higher frequency of deep convection.

Profiles of latent heating. **TRMM products have provided the first comprehensive estimates of how rainfall is directly related to latent heat release in the atmosphere, and how that heating is distributed in the vertical (Fig. 4),** a key characteristic in understanding the impact of tropical rainfall on the general circulation of the atmosphere. Based on hydrometeor vertical structure information from PR and TMI and model-based cloud information, TRMM scientists have derived climatologies of latent heating profiles (Olson et al. 1999, 2006; Tao et al. 2004, 2006) for analysis and comparison with global models. TRMM data have quantified changes in radiative and latent heating in the Pacific region in response to the different phases of ENSO (L'Ecuyer et al. 2006) and have revealed a top-heavy heating profile associated with large stratiform-rain contributions as part of the MJO (Morita et al. 2006).

Table 2. Highlights of selected peer-reviewed research during 2005-2006 using TRMM data.

• **Regional climate variations** Berg et al. 2006 (Journal of Applied Meteorology)	Examines regional biases in rainfall estimates using TMI and PR. Differences in rainfall between the two instruments are highly correlated with column water vapor. Differences in rain detection are most prominent along midlatitude storm tracks. Over the East China Seas, cloud systems that are below the PR threshold are frequently identified as rain by TMI, a possible affect of aerosols.
• **Precipitation Feature Database** Liu and Zipser 2005 (Journal of Geophysical Research–Atmospheres)	Used a University of Utah TRMM Precipitation Feature database to identify tropical deep convection with overshooting tops. They found that only 1.3% of convective systems reach 14 km height and that these overshooting storms are more prevalent over land, especially over central Africa, Indonesia, and South America. (See also: Cecil et al. 2005, Nesbitt et al. 2006, Zipser et al. 2006)
• **Tropical cyclones** Chen et al. 2006 (Monthly Weather Review)	Used TMI rainfall in tropical cyclones to examine the asymmetries that arise due to vertical wind shear. The asymmetries increase with shear, but decrease with increasing storm intensity. (See also: Atlas et al. 2005, Benedetti et al. 2005, Kodama and Yamada 2005, Braun 2006, Jiang and Zipser 2006, Li and Fu 2006, Ma et al. 2006)
• **Tropical dynamics** Masunaga et al. 2006 (Journal of Atmospheric Sciences)	Data from TRMM PR and VIRS, analyzed in the frequency-wavenumber domain to identify equatorial wave modes, indicate a clear relationship between the MJO and Kelvin waves and suggest that a sequence of convective events coupled with linear waves plays a critical role in MJO propagation. (See also: Back and Bretherton 2005, DelGenio et al. 2005, Rapp et al. 2005, Morita et al. 2006)
• **Lightning** Petersen et al. 2005 (Geophysical Research Letters)	Used TRMM PR and LIS data to show that, on a global scale, the relationship between precipitation ice water path and lightning flash density is relatively invariant between land, ocean, and coastal regimes, indicating that lightning may be useful for retrieving ice water content. (See also: Petersen et al. 2006, Takayabu 2006)
• **Human impacts** Lin et al. 2006 (Journal of Geophysical Research–Atmospheres)	They find that the dynamical effects of aerosols from biomass burning invigorates convection, leading to higher clouds, enhanced cloud cover, and stronger rainfall. They suggest that the accelerated burning for agriculture and resulting enhancement of aerosols may account for an observed positive trend in Amazonian rainfall. (See also: Chagnon and Bras 2005, Wu et al. 2006, Bell et al. 2007)
• **Winter precipitation systems** Yamamoto et al. 2006 (Journal of Geophysical Research–Atmospheres)	Used TRMM PR and VIRS to examine the characteristics of winter precipitation over the western Pacific near Japan associated with winter extratropical cyclones and fronts and cold air outbreaks. TMI frequently misses precipitation in cold air outbreaks because of their shallow, isolated nature while the PR more frequently misses weak precipitation from fronts because of its low sensitivity.
• **Global models** Dai 2006 (Journal of Climate)	Compared precipitation from 18 coupled climate models to TRMM and found that most models produced too much convective and too little stratiform precipitation in the tropics, biases that are linked to an unrealistically strong coupling of tropical convection to local SST. In many of the models, the convection starts too early in the day and occurs too frequently at reduced intensity compared to TRMM. (See also DelGenio et al. 2005, Lau et al 2005, Zhang and Mu 2005)
• **Sensor intercomparisons** Tran et al. 2005 (Journal of Atmospheric and Oceanic Technology)	Compares Ku-band backscatter cross-section measurements from PR with altimeter measurements from Jason-1 and Envisat and finds a consistency in the dependencies upon model wind speed estimates and significant wave heights. Because of TRMM's absolute calibration, observed relative offsets in radar cross sections can be used to indirectly calibrate measurements from Jason-1 and Envisat. (See also: Chan and Gao 2005, Tournadre and Quilfen 2005, Nalli and Reynolds 2006, Wen et al. 2006).
• **Algorithm development** Olson et al. 2006 (Journal of Applied Meteorology and Climate)	Describes a revised Bayesian algorithm (Version 6 of the TMI algorithm) for estimating surface rain rate, convective rain proportion, and latent heating profiles from passive microwave observations over ocean. The algorithm utilizes an expanded database of cloud-radiative model simulations. (See also: Chandrasekar et al. 2005, McCollum and Ferraro 2005, Chiu and Petty 2006, Viltard et al. 2006)

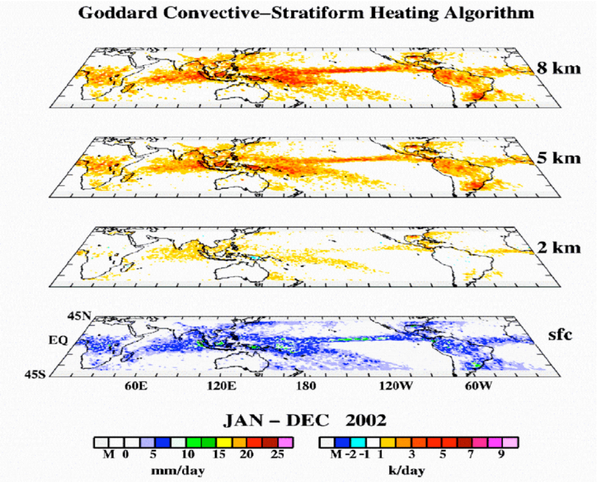

Fig. 4. Latent heating as a function of altitude for 2002 based on CSH algorithm.

Tropical dynamics and the MJO. **TRMM data has yielded new insights into the dynamics of the MJO, convective systems, and hypotheses on the dynamics of convective-climate feedbacks (see highlight in Table 2 for** Masunaga et al. 2006). Rapp et al. (2005) and Del Genio et al. (2005) examined cloud and precipitation relationships with SST and their results suggest that the climatic behavior of observed convective clouds is intermediate between the extremes required to support the thermostat and adaptive iris hypotheses.

Improved climate simulations. **TRMM information has led to improved simulations of the hydrologic cycle, climate characteristics, and the representation of convective systems.** TRMM rainfall data has been used to validate global climate models (Fig. 5; see Dai 2006, Table 2) and to improve the cumulus parameterization in the NCAR Community Climate Model (Zhang and Mu 2005). A parameterization of convective detrainment-precipitation partitioning based on observed TRMM behavior has been implemented in a GCM and found to imply a nearly neutral cloud feedback (Del Genio et al. 2005). TRMM data have also been used by Lau et al. (2005) to validate GCM results using various autoconversion rates, with results clearly indicating the need for a more sophisticated parameterization approach taking into account various types of rainfall (convective, stratiform, etc.).

Impact of humans on rainfall climatologies. **TRMM PR data have been used to identify rainfall anomalies possibly associated with human impacts on the environment (see Lin et al. 2006, Table 2).** The unique combination of TMI, PR and VIRS data has allowed for critical observations to be made as to the relation between aerosols (including pollution), land-use change, and rainfall. Deforestation in the Amazon basin causes dramatic changes in climatological rainfall patterns with more rain over deforested areas (Chagnon and Bras 2005). The Three Gorges Dam in China significantly raised water levels and increased the width of the river, leading to a shift in precipitation patterns by increasing rainfall to the north and decreasing rainfall over the river (Wu et al. 2006). Changes in rainfall in urban environments (Shepherd et al. 2002; Shepherd and Burian, 2003) have been found to be related to the urban heat island and variations in roughness. On regional scales, Bell et al. (2007) found that a midweek increase in summer rainfall amount, rainfall area, and storm height in the southeast U. S. and a midweek decrease over nearby Atlantic waters corresponded to a similar midweek peak in particulate concentrations.

2.2 Convective systems and tropical cyclones

Convective systems characteristics. TRMM PR, TMI, VIRS, and LIS supply information for a Precipitation Feature (PF) database, created by the University of Utah, **that provides a definitive climatology of the distribution of convective system characteristics from horizontal size, depth, and extreme events (see Liu and Zipser 2005, Table 2),** and how these characteristics are distributed as a function of geography, orography, time of day, etc. (Nesbitt et al. 2000). The PF database has been used to examine the regional variability in rain area and maximum horizontal extent (Nesbitt et al. 2006). The geographic locations of very intense convective storms showed strong regional preferences for certain land areas (the south-central U.S., southeast South America, and equatorial Africa) while they were rare over oceans (Zipser et al. 2006). Cecil et al (2005) found that the largest storms are largely independent of the most

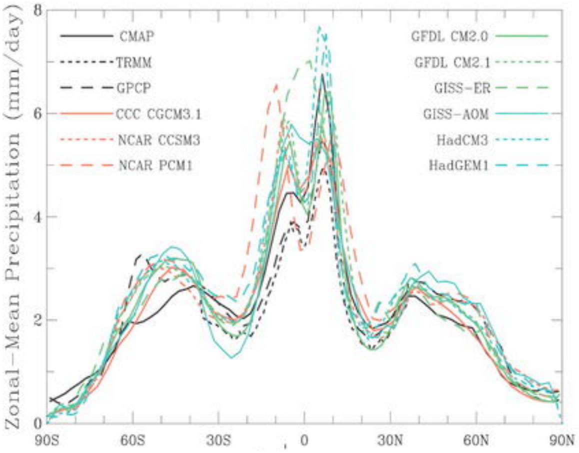

Fig. 5. Latitudinal distribution of zonally averaged annual-mean precipitation from three observational analyses (CMAP, GPCP, TRMM) and simulations by 9 GCMs. (From Dai 2006)

intense ones and the set of storms producing the most rainfall is a convolution of the most intense and largest storms.

Tropical cyclones. **TRMM TMI and PR data have been used to establish for the first time key characteristics of the distribution and variation of rainfall in tropical cyclones as a function of intensity, basin, stage of development, and environmental conditions (e.g., shear) (Lonfat et al. 2004, Chen et al. 2006).** TRMM PR and TMI data have been used to derive vertical profiles of precipitation ice and liquid water content in tropical cyclones (Jiang and Zipser 2006). Li and Fu (2006) used TMI rainfall and Quikscat winds to show that in the tropical west Pacific, cyclogenesis can be initiated by Rossby wave energy dispersion associated with another pre-existing cyclone. The ability of TRMM to see within cloud systems enables it to detect the eye of topical cyclones much more often than with infrared sensors (89% vs. 37%, Kodama and Yamada 2005) and observations of deep convective towers in the eyewall have been linked to subsequent rapid deepening of storms (Kelley et al. 2004). TRMM data have also been used to validate mesoscale model simulations of hurricanes (Braun 2006) and have been demonstrated to have positive impacts through data assimilation on simulations (Atlas et al. 2005, Ma et al. 2006) and forecasts (Benedetti et al. 2005) of tropical cyclones.

2.3 Measurement advances

Improvement of algorithms. Comparison of TMI and PR rainrates has led to **increased understanding of differences between, and therefore improvements to, these retrievals and those for all passive microwave sensors** (see Berg et al. 2006, Table 2; Nesbitt et al. 2004, Masunaga and Kummerow 2005). In addition to research related to the facility algorithms, work has also progressed on experimental algorithms. Chiu and Petty (2006) describe an alternative Bayesian algorithm that yields not just a single rain rate, but rather a continuous probability distribution of rain rate. Particle size distribution parameters are being retrieved from the PR-measured attenuation and reflectivity values (Chandrasekar et al. 2005).

Combined instrument algorithm. The **first active-passive rain algorithm applied to satellite data** was developed for TRMM and has been applied since launch (Haddad et al. 1997). In relation to the separate PR and TMI algorithms, the trio have been used to isolate differences and the physical basis for those differences. This has allowed the combined PR/TMI algorithm to mature during TRMM's lifetime. In recent years, algorithms have been developed that use the PR reflectivity profile information to improve the rainfall and hydrometeor retrievals from the TMI (Grecu and Olson 2006, Viltard et al. 2006).

Multi-satellite analyses. With the TRMM satellite producing the best instantaneous rain estimates, those estimates have been used to calibrate or adjust rain estimates from other satellites to provide analyses at higher time resolution than available from one satellite (Adler et al. 2000). Recently, **new products are providing a 3-hr standard TRMM Multi-satellite Precipitation Analysis product (Huffman et al. 2005) and other novel approaches to combine satellite rain information (Joyce et al. 2004).** The TRMM multi-satellite rain products are now being used, for example, to validate models (Bauer and Del Genio, 2005), estimate rainfall associated with tropical cyclones, and identify regions susceptible to floods and landslides (Hong et al. 2006b).

Rainfall assimilation. **TRMM has provided major impetus for the data assimilation community to explore innovative approaches to use rainfall data to improve atmospheric analyses and forecasts**. These new techniques range from variational rainfall assimilation using the model as a weak constraint (Hou et al. 2001, 2004) to super-ensemble forecasting techniques (Krishnamurti et al. 2001, Kumar and Krishnamurti 2006). TRMM research has provided clear demonstrations of the benefits of rainfall assimilation in a wide range of situations (Hou et al. 2001, 2004; Pu et al. 2002; Marecal et al. 2002; Aonashi et al. 2004; Pu and Tao 2004; Benedetti et al. 2005; Ma et al. 2006).

2.4 Applied research

Hydrological/land surface applications. **TRMM-based multi-satellite data are being used as input into hydrological and land surface models, including LDAS systems, to better understand land-atmosphere interactions on scales of days to years (Rodell et al. 2004) and study variations in river runoff (Fekete et al. 2004).** These same data are also being used by USAID/NOAA/USGS to monitor crops in Central America and elsewhere, and as input into river forecast models in South Asia and other locations (Tokar [USAID] personal communication). Providing information on rainfall intensity and duration, the TRMM multi-satellite precipitation product has made possible a global flood and landslide monitoring system (Hong et al. 2006b). Passive microwave information from TMI has been used to infer soil moisture and fluxes at large basin scales (Gao et al. 2006, Shi et al. 2006), to assess the impact of vegetation on soil moisture retrievals, and for assimilation into numerical models (Crow et al. 2005, Drusch et al. 2005).

Sea surface temperatures. With its 10 GHz channel on TMI, TRMM observations produced the **first SST data through clouds (Wentz, 2000).** These data have been used for numerous applications including for climate monitoring (Stammer et al. 2003, Reynolds et al. 2004) and the identification of cold wakes behind tropical cyclones. Chelton (2005) used TRMM SSTs and Quikscat winds to compare the observed coupling of surface wind stress and SST to that in the ECMWF global model, allowing the identification of potential deficiencies in the model processes. TRMM SST data, in combination with other data sets, have been used to examine the annual and inter-annual variability of Kuroshiro intrusions into the South China Sea (Caruso et al 2006) and the heat transport by mesoscale eddies in the Kuroshiro region (Qiu and Chen 2005), as well as to detect "hot spots" for fishing of albacore tuna in the northwestern Pacific Ocean (Zainuddin et al., 2006).

Sensor intercomparisons. **TRMM data is regularly used to improve and validate measurements from other satellite remote sensors (see Tran et al., Table 2).** TRMM SSTs have been compared to measurements from ASTR, AVHRR, AMSR-E, and MODIS (Chan and Gao 2005; O'Carroll et al. 2006a, b; Nalli and Reynolds 2006). TMI data was used by Wen et al. (2006) to calibrate brightness temperatures from the Indian Space Research Organization's Multi-frequency Scanning Microwave Radiometer on their Oceansat-1 platform. PR data was also used along with data from Seawinds to assess the impact of rain on wind vector retrievals and derive a new rain flag to indicate rain-affected data points (Tournadre and Quilfen 2005).

2.5 Operational use of TRMM data

Early in the TRMM mission, the TRMM data system (TSDIS) began to produce real-time TRMM products in a "best effort" mode. Numerous users requested through NASA HQ access to the real-time data. Other organizations, most notably NRL-Monterey, produced value-added operational TRMM products for their users. The end result has been an enormous use of TRMM data for operational forecasting, applied science, and real-time research. The recent National Academy report (Section 2.6) describes numerous operational uses of TRMM data in the U.S. and internationally. The main uses of real-time TRMM data will be summarized in this sub-section.

Monitoring of tropical cyclones. **TRMM data (primarily TMI data) are used by both NOAA (National Hurricane Center [NHC]) and DoD (Joint Typhoon Warning Center [JTWC]) in the U.S. and tropical cyclone centers in Japan, India, Australia, etc. for detecting the location and intensity of tropical cyclones. In 2004, more than 600 tropical cyclone fixes were made using TRMM by these agencies.** Because of TRMM's finer spatial resolution (compared to SSM/I), these fixes are usually considered among the most accurate of satellite-based locations. In addition, TRMM's orbit (always in the tropics) provides data at different times than the sun-synchronous microwave instruments with its best sampling in the cyclone-important 10-37° latitude bands. TRMM data are also used (often in time histories with other satellite data) to detect changes in convection, eyewall formation and other features related to intensity change. TRMM data are frequently mentioned in warning center discussions.

Rainfall monitoring. **Because of its near real-time availability, the TRMM-based Multi-satellite Precipitation Analysis (TMPA) is being used by various entities in the U.S. interested in detecting floods, and is used by numerous groups and countries globally, where conventional information is often lacking, to detect floods and monitor rain for agricultural uses.** NRL-Monterey and NOAA/NCEP use TRMM data as a key part of their multi-satellite rain estimates, as well as NOAA NESDIS's Tropical Rainfall Potential (TRaP) program used to estimate flood potential in hurricanes.

Numerical weather prediction. NCEP has been assimilating TRMM data into its global numerical weather prediction system since October 2001. Although the effect of including TMI on NCEP model forecast skill scores is small, there is evidence of modest improvements. JMA and the 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.** ECMWF is currently assimilating SSM/I data operationally and, because of TRMM's extension in 2005, is planning on assimilating TMI data. ECMWF uses PR data to independently determine the error characteristics of input rainfall information from all satellite microwave sensors. Florida State University (FSU) has had significant success in assimilation of TRMM data into their models, which are key elements of their Super Ensemble approach. The ensemble is trained on satellite precipitation data, including the high quality TRMM estimates.

Air Traffic advisories. **LIS data are provided directly to the NOAA/NCEP Aviation Weather Center (AWC) and also made available to Forecast Offices to identify convective weather hazards (oceanic, in particular).** AWC forecasters responsible for convective and international SIGMETs (significant meteorological advisories) overlay LIS data with conventional visible and infrared imagery to better understand which convective cells have increased likelihood of turbulence.

2.6 National Academy Review

At the request of NASA, the National Academies (NA) has completed an assessment of the scientific accomplishments of TRMM and the benefits of extending the TRMM mission. The key findings are summarized in this section.

A key conclusion from the Executive Summary of the NA report: "*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.*"

The NA report summarized the <u>research reasons</u> for continuation of TRMM from their viewpoint in Conclusion 4.3 from that report: ***"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 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 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."*

In terms of <u>operational use</u> of TRMM data, the NA panel stated that: "***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."

3. SCIENCE WITH AN EXTENDED TRMM MISSION

The overall science objective of an extended TRMM mission is *to determine the time and space varying characteristics of tropical rainfall, hydrometeor structure and associated latent heating for convective systems and storms, and how these characteristics are related to variations in the global water and energy cycles.* This TRMM goal is at the heart of NASA's Earth Science strategy and the answering of key science questions, primarily for the Weather and the Water and Energy Cycle focus areas, i.e., *"How are global precipitation, evaporation and the water cycle changing?", "How will water and energy cycle dynamics change in the future?", and "What are the consequences of changes in water availability and weather for human civilization?"* Having a long, accurate record of quasi-global precipitation characteristics is critical to achieving NASA's Earth Science goals. Extension of TRMM for the next four years will provide that information and science to NASA and the world research community.

Table 3 relates expected, key TRMM contributions to each of the NASA Strategic Questions and also outlines to which applied science areas TRMM will contribute significantly. Obviously from the table, TRMM's contributions are critical to the NASA program and a loss of information from TRMM would create a distinct weakness in the observation of weather and the water cycle and, therefore, NASA's research program.

NASA's research program and TRMM are also closely linked to the national scientific priorities identified by the U.S. Climate Change Science Program (CCSP) and to international coordination through the World Climate Research Programme (WCRP) - in particular the Global Energy and Water Experiment (GEWEX) and the Climate Variability and Predictability (CLIVAR) program. In fact, it is noteworthy that it was only after TRMM had begun to fulfill its promise that the U. S. Global Change Research Program (USGCRP) focus (FY2000 Our Changing Planet) evolved to support the Water Cycle as a discreet program element. The prominence of the Water Cycle in the current Climate Change Science Plan and in the NASA science questions above is due, in large part, to the scientific success and longevity of TRMM.

The TRMM results already described in Section 2, valuable though they are, are incomplete in many instances. For example, the nine-year climatology needs a larger database before we can have as much confidence in the precipitation variability as we now have in the mean values, or in regional statistics as confidently as we now have in global statistics. Climatologies of the tails of distributions, i.e., the climatologies of more rare extremes, require a longer data record. The human influences on precipitation, related to changes in land surface characteristics (urbanization, deforestation) and anthropogenic aerosols, are uncomfortably close to the noise level without a longer database. Hypotheses on external (environmental) and internal (convective/stratiform heating and potential vorticity dynamics) influences on tropical cyclone formation and intensification, and their inter-annual variability, require additional cases and years for secure conclusions.

Extension of TRMM to its fuel limit (~2012) will nearly close the gap that would otherwise exist in the global rainfall data record between the end of TRMM and the launch of GPM (2013). The current TMPA (3B42) 3-hourly near-global multi-satellite precipitation product is a prototype for the future GPM mission product, combining information from the current constellation of microwave sensors and, when needed, geostationary infrared sensors, and using the TRMM PR as a calibration reference. A similar product will be produced in the GPM era using the GPM core satellite as the calibration reference. Minimizing the gap between TRMM and GPM will extend the rainfall record to improve the detection of trends that relate to changes in the global water and energy cycles.

In the following sub-sections, the basis for proposed research with an extended TRMM mission and the associated science questions are described.

3.1 Improved climatology of precipitation characteristics

Science Question 1: What is the fine-scale (horizontal, ~25 km) climatology of precipitation characteristics (mean surface rain, diurnal cycle, vertical structure) on a monthly to seasonal basis?

The value of the relatively short (in climate terms) TRMM dataset for climate research increases rapidly with every year of added observations. 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 with 9 years of data. Precipitation is an episodic process with small-scale structure, and is therefore much more difficult to characterize than a continuous field such as temperature. While zonal averages of surface rain over the ocean are now known to within ~10%, on finer scales such as at the resolution of a climate model (~2.5°), the TRMM rainfall algorithms still disagree by relatively larger values (Nesbitt et al. 2004). Continued improvement of algorithms and exploration of algorithm differences over the proposal period will lead to further convergence.

Sampling problems become particularly severe when attempting to characterize such features as the diurnal cycle, convective/stratiform separation, and characterizing relatively rare, but important, extreme events. A comprehensive climatology of these characteristics must consider their variability regionally, by season, by type of disturbance, and in relation to other factors such as MJO or ENSO phase. The TRMM database must be extended to establish the stable statistics needed to define the characteristic features of the tropical hydroclimate. The improved definition of these long-term means is critical for closing the global and regional water budgets, for validation of climate models, and for benchmarking longer satellite-based precipitation analyses such as the Global Precipitation Climatology Project (GPCP) (Adler et al. 2003).

TRMM will provide refined benchmark climatologies of surface rain, diurnal cycle and vertical structure for global and regional water cycle closure and validation of climate models.

3.2 Inter-annual variations of precipitation

Science Question 2: How do the characteristics of tropical precipitation (mean surface rain, hydrometeor structure, latent heating profiles, lightning activity, etc.) vary inter-annually in relation with ENSO and other phenomena?

NASA Strategic Science Questions	TRMM Contributions to NASA Strategic Science Questions in the Next 5 years	Relevant Applied Science Areas
*How are **global precipitation**, evaporation, and the **water cycle** changing? **(variability)***	-Improved climatology of precipitation characteristics (e.g., diurnal variations, vertical structure, extremes) at finer resolutions -Diagnosing/testing of inter-decadal change and trend-related processes requiring detection of subtle changes in rain characteristics	Water Management, Agricultural Efficiency
*What are the effects of clouds and surface **hydrologic processes** on Earth's climate?* *How do ecosystems, land cover, and biogeochemical cycles respond to and affect global change?* *How do atmospheric trace constituents respond to and affect global environmental change?* ***(response)***	-Refined latent heating as a function of altitude (key climate system driver) -Assessment of impact of humans (e.g. cities and aerosols) on rainfall climatologies and precipitation processes -Robust convective systems characteristics (space, time, cloud type) and lightning characteristics -Hydrological applications over land (testing TRMM data in land data assimilation systems, basin scale assessments, and budget closure estimates)	Water Management, Agricultural Efficiency, Public Health, Coastal Management, Air Quality
*How are variations in local weather**, precipitation** and **water resource**s related to global climate variation?* *What are consequences of land cover and land use change for human societies and sustainability of ecosystems?* ***(consequences)***	-Inter-annual variations of precipitation (e.g. longer, continuous TRMM data records will better characterize tropical seasonal-inter-annual climate variability in general and the El Niño-Southern Oscillation (ENSO) cycle in particular. -Assessment of impact of humans (e.g. cities and aerosols) on rainfall climatologies and precipitation processes	Water Management, Agricultural Efficiency, Public Health, Disaster Management, Coastal Management
How can weather forecast duration and reliability be improved? *How can predictions of climate variability and change be improved?* *How will **water cycle** dynamics change in the future?* ***(prediction)***	-Improving analysis and modeling of global water/energy cycle to advance weather/climate prediction capability (e.g. precipitation assimilation, process studies) -Continued improvement of weather forecasting, especially for monitoring/forecasting the intensity of tropical cyclones and the intensity of rainfall they yield. (NOAA, DoD, WMO Centers -Continued TRMM 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). This includes use of PR/TMI in calibrating similar data from other microwave sensors and contributes to improved global, as well as tropical, precipitation monitoring and prediction. (NOAA, JMA, ECMWF, USAID, USDA) -Continued sea surface temperatures in cloudy environments for hurricane forecasting	Water Management, Agricultural Efficiency, Public Health, Homeland Security, Energy Management, Disaster Management, Coastal Management, Air Quality, Aviation

Table 3. Matrix mapping for continued TRMM operations to key NASA Science Questions and Applied Science Areas. The matrix is consistent with NASA 10-year outcome goals to: (1) enable seasonal precipitation forecasts at 10-100km resolution with greater than 75% accuracy, (2) balance global water and energy budgets to within 10%, (3) decrease hurricane landfall uncertainty from+/- 100 km in 3 day forecasts, (4) enable 7-10 day forecasts at 75% accuracy, (5) enable 10-year climate forecasts---Source: NASA Earth Science Research Plan-11/02/04 (Draft)

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 inter-annual 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's land-ocean-atmosphere climate system.

The most extreme and widespread year-to-year variations in tropical rainfall are associated with the ENSO 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 rainfall processes. TRMM provides a reliable quantification of the evolving rainfall field and crucial information on latent heating profiles. The nine-year TRMM record that now exists includes the later stages of the major 1997-1998 El Niño, the weak 2002-2003 event, and the most recent 2006-2007 event. The differences between these events illustrate their variability in intensity and character from event to event. While these three realizations are useful for preliminary studies, they are insufficient for characterization of the hydroclimatic aspects of ENSO and other inter-annual variations. Since El Niño recurs at irregular intervals of two to seven years, there is a high probability of one or more additional El Niño occurrences between 2007 and 2012. Continuous TRMM observations from 1998 into the GPM era would provide a unique and valuable continuous record for characterization of the ENSO cycle.

Extension of TRMM will better define ENSO-related (and other) inter-annual variations in precipitation characteristics for increased understanding and testing of climate simulations and seasonal-to-annual forecasts.

3.3 Diagnosing/testing of inter-decadal changes and trend-related processes

Science Question 3: What is our level of confidence in variations (inter-annual and inter-decadal) of large-area precipitation means noted in long-term (~27 year) data sets.

Science Question 4: What is the relation between spatially integrated tropical precipitation and surface temperature on inter-annual time scales, and how is that related to possible global warming/water cycle acceleration scenarios?

Even with a mission extension of 2-4 years, TRMM's potential total length of record by itself is obviously limited in assessing precipitation changes over inter-decadal periods or longer. On the other hand, the TRMM data could be the start of a long-term record of radar/microwave radiometer data if linked to GPM in the future. However, even a modest extension of the TRMM record will be useful in terms of helping to evaluate longer time period changes. For example, Lau and Wu (2006) observed a shift in the probability distribution functions of rainfall in both the GPCP and CMAP long-term data sets. This shift included a positive trend in the occurrence of heavy and light rainfall and a downward trend in the occurrence of moderate rainfall. The shorter, but independent, 9-year TRMM record is being used to assess the accuracy of variations and trends in the 27-year GPCP precipitation analysis by examining the overlapping period (1998-present). Especially important is the use of the PR information to confirm or question inter-annual to inter-decadal variations evident in the passive microwave record, which extends back to the middle of 1987 using the SSM/I instrument.

In addition, quantifying the associated *net integrated changes* to water and heat balance over the entire tropical oceanic or land sectors remains an observational challenge. While ENSO events are clearly not a climate change phenomena, they are important perturbations to the tropical and global energy and water balance and are accessible science "targets" for TRMM. Earlier pre-TRMM investigations (Soden 2000, Robertson et al. 2001) have suggested that, at least over tropical oceans, passive microwave emission and scattering techniques both yield positive correlations with SST. On the other hand, Su and Neelin (2003) have used a tropical climate model of intermediate complexity to argue that a poor correlation exists between tropical average SST anomalies and precipitation anomalies. It is essential to document these integrated responses, to understand the physical processes at play, and to validate our ability to model these large climate variability signals. TRMM is still in the process of providing resolution to this issue.

Every year that the TRMM mission can be extended helps reduce sampling error in isolating not only ENSO events, but also in narrowing uncertainties in precipitation trends and low frequency behavior. In turn, this helps narrow uncertainties in evaporation and moisture transport in closing the water budget.

TRMM will provide a lengthened record of independent surface rain and vertical structure information necessary to diagnose critical, subtle variations and changes related to climate change scenarios.

3.4 Improving analysis and modeling of the global water/energy cycle to advance weather/climate prediction capability

Science Question 5: What are the key processes linking tropical precipitation systems to monsoon, intraseasonal oscillations, and ENSO dynamics in producing climate variations in the global water and energy cycles?

Science Question 6: How do we devise optimal data assimilation procedures to maximize the information content from space radar and radiometer precipitation measurements to improve climate analysis and numerical weather prediction?

Data assimilation is a statistical estimation procedure that integrates TRMM precipitation and moisture observations with model information to provide a physically consistent estimate (i.e. analysis) of the global water and energy cycles. But at the present time, global analyses have considerable uncertainties in basic hydrological variables such as precipitation and evaporation, especially in the tropics.

Since the launch of TRMM there has been a growing body of evidence showing the benefit of assimilating rain rates from passive microwave radiometers for improving both analyses and forecasts provided by mesoscale and global numerical weather prediction systems (Hou et al. 2001, 2004; Pu et al. 2002; Marecal et al. 2002; Aonashi et al. 2004; Pu and Tao 2004; Benedetti et al. 2005; Ma et al. 2006). In addition, Krishnamurti et al. (2001) and Kumar and Krishnamurti (2006) have demonstrated the value of microwave rainfall data in multi-analysis and multimodel superensembles for achieving greater forecast skills than any of the ensemble members. With its unique low-inclination, non-sun-synchronous orbit, TRMM provides crucial rainfall measurements filling the gaps between the current fleet of polar-orbiting passive radiometers during a typical 6-12 h data assimilation window. The additional sampling by TRMM yields more accurate climate analyses in terms of the atmospheric circulation, moisture distribution, and cloud-radiation energy fluxes in the tropics (Hou et al. 2001). Rainfall assimilation provides global analyses that are dynamically consistent with observed precipitation, which are crucial for breaking a major roadblock in understanding the interplay between tropical convective systems, monsoons, and MJOs on intraseasonal time scales, and the global impact of ENSO variability on inter-annual time scales (see Fig. 6 for improved MJO simulation results). The improved analyses are also capable of upgrading weather forecasting skills, leading to better predictions of severe storms and extreme weather events in the tropics.

The data assimilation and NWP community is only in the early stages on the learning curve in developing techniques to make effective use of space-based rainfall measurements. For instance, research is just underway to examine ways to assimilate TRMM/PR rain rates, reflectivity profiles, and the associated latent heating products. The launch of CloudSat and CALIPSO in 2006 now provides a unique opportunity to test the value of the combined use of cloud and rain profile information to improve climate analyses and forecasting skills. But the anticipated progress in this area at operational NWP centers is contingent upon having TRMM data in the near-real-time observation data stream. In the U.S., the continued TRMM real-time data availability will provide crucial impetus for the NASA/NOAA/DOD Joint Center for Satellite Data Assimilation (JCSDA) to develop cloud/precipitation assimilation algorithms for operational weather forecasting. Moreover, as NWP agencies experiment with radiance assimilation in rainy regions in the coming years, the TRMM PR will have a critical role in precipitation forecast validation.

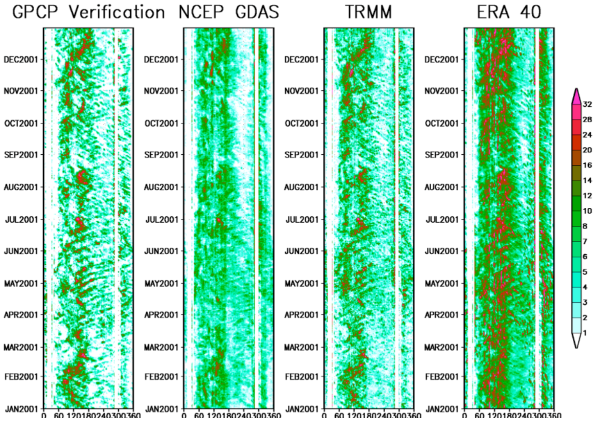

Fig. 6. Comparison of MJO signals in tropical oceanic precipitation (10N-10S) between GPCP satellite-gauge estimates and global analyses from the operational NCEP/GDAS, the NASA/TRMM re-analysis and ECMWF re-analysis (ERA-40) for 2001. The TRMM re-analysis, which assimilates 6h TMI and SSM/I surface rain data, is much better at capturing the intensity and propagation of tropical rain systems than other analyses that do not assimilate satellite rainfall data.

Continuation of TRMM will enable a 10-plus year analysis of the complete global water and energy

cycle through the use of global data assimilation systems and the assimilation of TRMM precipitation information.

3.5 Tropical cyclone processes

Science Question 7: What are the primary physical processes relating inner-core convection to tropical cyclone intensity change?

Science Question 8: What are the rainfall, convective structure and microphysical characteristics of tropical cyclones and how do they vary with storm strength, geographic location, and environmental conditions (e.g., shear)?

Data from TRMM have stimulated advances in tropical cyclone research and understanding. The PR is the only space-based method for quantifying the vertical structure of these convective systems and it 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. For example, the connection between convective bursts (exceptionally deep and energetic convective towers in the eyewall) and sudden intensification is a critical research topic. A study from a limited sample of storms (Kelley et al. 2004) suggests that when convective "hot towers" exceed 14.5 km height, there is a 71% probability that the storm will intensify. However, characterizing and understanding the relationship between these convective bursts and tropical cyclone intensification will require a longer record than is currently available. The narrow swath of the PR and short-lived nature of convective bursts strongly argues for mission extension to increase sample sizes for statistical analyses.

Factors controlling the horizontal distribution of rainfall in tropical cyclones are also poorly understood, yet freshwater flooding accounts for the majority of tropical cyclone deaths. Published climatologies of surface rain rate from early TRMM data (Lonfat et al. 2004, Chen et al. 2006) have shed light on the radial distribution of rainfall as a function of storm intensity and how rainfall asymmetries are related to vertical wind shear. With improved accuracy of forecast track and storm propagation speed, rain accumulation forecasts (from a model known as the rainfall climatology and persistence model or R-CLIPER) have recently become operational based on these results. The vertical structure information from the PR indicates the distribution of latent heat release in tropical cyclones and further research with TRMM PR data will give a better understanding of the vertical structure of precipitation in tropical cyclones. Whereas research aircraft radar can provide some data of similar resolution, a satellite-based system is required to observe the precipitation during all stages in the hurricane life cycle and in regions where research aircraft are not available. 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 these statistics since more details of the many influences from intensity, location, track speed, and other factors on the rainfall and vertical structure could then be included.

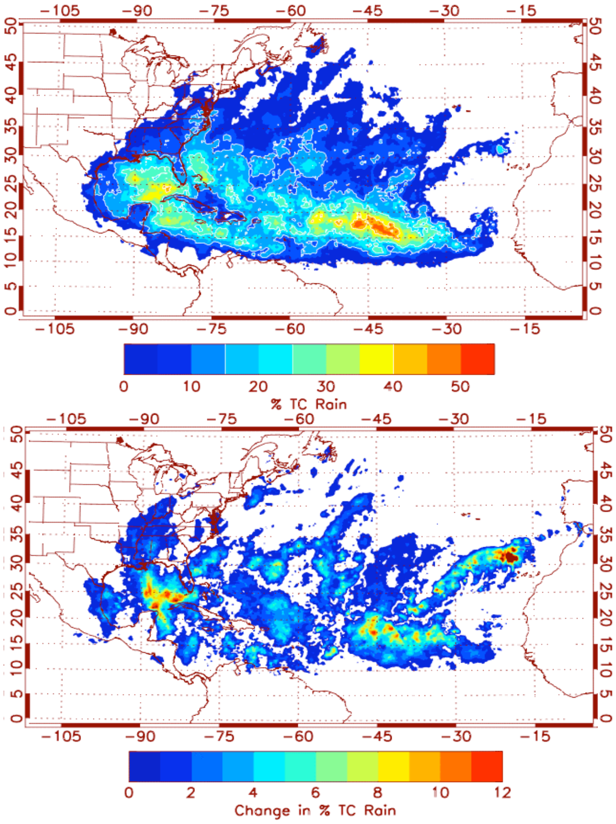

Fig. 7. (a) The percentage of June-November rainfall from tropical cyclones for the period 1998-2004, showing that up to 30-50% of Atlantic rainfall north of 10°N derives from tropical cyclones. (b) The change in the tropical cyclone rainfall percentage that results from including data from 2005 in the climatology.

As an example of the impact of adding additional years of data on the characterization of extreme events such as hurricanes, consider the problem of quantifying the percentage of June-November rainfall that occurs in association with hurricanes. Using the TRMM multi-satellite precipitation analysis, the accumulated rainfall can be calculated for each hurricane in the Atlantic in a given year and then added together to get the total hurricane rainfall for that year. The percentage of rainfall coming from hurricanes is then estimated by comparing the accumulated hurricane rainfall over several years to the total overall rainfall for the same period. Figure 7a shows the climatology of the percentage of rainfall from hurricanes for the 7-year period 1998-2004, indicating that hurricanes account for up to 30-50% of Atlantic rainfall in some regions. Figure 7b shows the change in that percentage that occurs if the year 2005 is included in the climatology and indicates local changes up to and even exceeding 12%. This large change occurs because of the substantial inter-annual variability of hurricane activity in the Atlantic and suggests that several more years of additional data are needed to stabilize the climatology calculations.

Continuation of TRMM will provide improved understanding of tropical cyclone formation and intensification processes through stable statistics of PR-based vertical structure, improved model simulations, and improved climatologies.

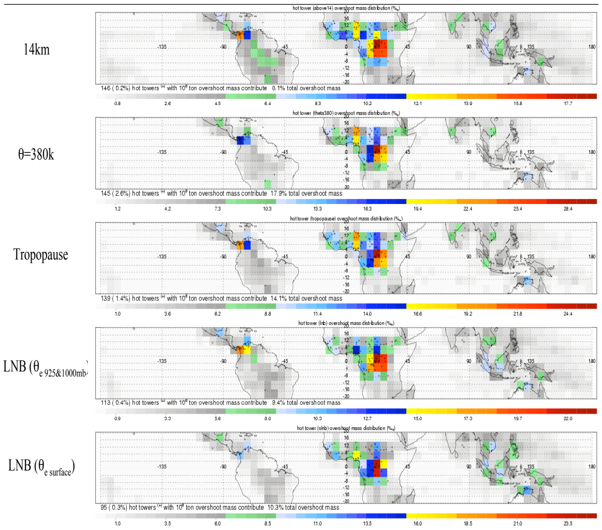

Fig. 8. Fractional contribution (parts per thousand) of each 5° square to total mass of precipitating ice from hot towers in the tropical tropopause layer for 5 years of TRMM PR data. Five different reference levels are used, with average height ranging from 14.0 – 16.8 km. For any definition of reference level, the dominance of land over ocean, and of tropical Africa over South America and Indonesia is clear.

3.6 Characteristics of convective systems

Science Question 9. What is the global distribution of intense convective storms and severe weather, and can their regional distributions and time variations be explained from dynamical, microphysical and/or other factors?

Science Question 10. What are the space and time distributions of extremes in convective intensity, surface rainfall rate and lightning and how are they related to large-scale seasonal, inter-annual and inter-decadal variations?

The nine years of TRMM data have been extremely important in determining numerous characteristics of convective systems and how they vary regionally, seasonally, and under different environments. However, the limited time record hampers close examination of these characteristics and is insufficient for looking at others. Climate consists not only of long-term averages, but of deviations from those averages, and in many cases it is precisely those more extreme deviations (especially where precipitation is concerned) that have the greatest impacts on humans. TRMM is uniquely capable of studying the incidence of extreme convection and severe weather over most of the planet. By definition, these events are infrequent, so definitive statistics of extremes require lengthy data records. The same holds true when trying to evaluate the regional rainfall contribution and diurnal cycle from relatively rare but hydrologically crucial mesoscale convective systems (Nesbitt and Zipser 2003), or when trying to evaluate how environmental characteristics (such as background thermodynamics or aerosols) can affect precipitation processes and diurnal cycles in a given region. The TRMM PR sampling of any given location is of order 15 times per month; so, much like with the hurricane rainfall climatology, additional years of data are required to make valuable statistics on diurnal cycles, annual cycles, and regional details.

A more fundamental research objective that requires the TRMM database of extremely strong storms is the mass exchange between troposphere and stratosphere. Pioneering research by Danielsen (1982, 1993) proposed the hypothesis that such intense storms control the water vapor distribution in the stratosphere by “freeze-drying” the ascending mass. Subsequent papers have proposed different mechanisms (e.g. Holton and Gettelman 2001, Hartmann et al. 2001). The TRMM data now show that the most extreme overshooting clouds are found over continents, notably Africa (Fig. 8). This is also the region on earth with the greatest mean annual flash density. These new results directly contradict conclusions from IR data, which favor the west Pacific and Indonesian regions studied by Danielsen and many others. While the dominance of such strong storms over Africa is probably secure, we have insufficient data to be able to define accurately the precise locations (the 5-degree box data are very noisy), the diurnal and seasonal cycles, and the environmental conditions that favor extreme rather than merely strong convection. The fact that the intense African convection may well be injecting the products of biomass burning and other pollutants into the stratosphere is potentially important to understanding global biogeochemical cycles. [If the alternative view prevails (that the west Pacific convection dominates), the air injected into the stratosphere would likely be very clean.]

Extension of TRMM will provide the data necessary for definition of statistics of occurrence of extreme convection and its role in troposphere-stratosphere exchange.

3.7 Hydrologic cycle over land

Science Question 11: How are hydrologic fluxes and states such as runoff, evapotranspiration, soil moisture, and groundwater recharge affected by changing precipitation patterns?

Science Question 12: Is the frequency of extreme hydrologic events such as droughts and floods changing?

TRMM provides the most advanced platform for satellite-based rainfall estimation over land due to the combination of active microwave (PR) with passive microwave (TMI), infrared (VIRS), and lightning imaging sensors (LIS). Accordingly, TRMM is a unique asset for studies of the hydrologic cycle over land, particularly since major fractions of the land area in key tropical river basins (e.g., the Amazon and Nile) contain few rain gauges. As such, the TRMM-PR is one of the most valuable instruments in space for analysis of the terrestrial hydrologic cycle, as it allows for determination and characterization of the errors and biases inherent to the other methods (IR, passive microwave, etc.) and provides results that can be extended to current and future (e.g. GPM) platforms. TRMM is also the key component of multi-satellite precipitation analyses, which are very important starting points for much land hydrologic work.

For example, a key unresolved science issue related to the hydrologic cycle over land is how changing precipitation patterns at multiple scales will translate into changes in hydrologic fluxes and states, such as runoff, evapotranspiration, soil moisture, and groundwater recharge. Recent analysis (Fekete et al. 2004) demonstrated a significant amplification of uncertainty in using precipitation fields from commonly applied global precipitation products (6, including TRMM) to determine spatially-distributed runoff, which ultimately is the source of renewable freshwater resources. Also, the global geography of runoff source areas shows nearly 20% of humankind with little or no access to renewable supply, a high degree of water scarcity, and economic hardship (Vörösmarty et al. 2005). Accurate assessment of renewable freshwater resources is critical to economic and social development and the entry point for making such estimates is accurate precipitation measurement. Understanding and predicting these changes is a key goal of the Global Land Data Assimilation System (GLDAS; Rodell et al. 2004), which uses TRMM-based multi-satellite data as input into several hydrological models.

As discussed above, extension of TRMM to 2010, or beyond, would significantly increase 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. In addition to global water budgets, a key terrestrial hydrologic science question is whether, when and where the frequency of extreme events such as droughts and floods is changing. This question can only be evaluated with continuous, long-term, accurate estimates of precipitation over land. Continuation of TRMM is critical for the advancement of the use of satellite precipitation information in land hydrology studies and applications.

Extension of TRMM will lead to improved global and regional simulation of land hydrologic processes through assimilation and resulting increased understanding and improved applications.

3.8 Impacts of humans on precipitation

Science Question 13: What is the quantitative aerosol-precipitation relation on a global or regional basis and the relative impact of pollution on those relations?

Science Question 14: How are the existence and strength of land-surface induced (e.g., deforestation, urbanization) precipitation anomalies related to the size of the modified land surface, seasonal climate, and aerosol environments?

Detecting the possible impact of human civilization on the precipitation component of the water cycle has been an unexpected research result of TRMM. Additional years of TRMM data would aid that definition and possibly even detect trends in that impact. The human impact research falls into two general areas, impact of pollution on precipitation in general and the impact of land-surface change on precipitation patterns.

Several studies using combined TRMM PR-TMI-VIRS data have suggested that aerosols, both natural and anthropogenic, play a pivotal role in precipitation processes (Rosenfeld, 1999, 2000; Ramanathan et al. 2001; Givati and Rosenfeld 2004; Andreae et al. 2004). A great deal of work remains because while most results (e.g. Rosenfeld 1999, 2000) suggest that aerosols reduce

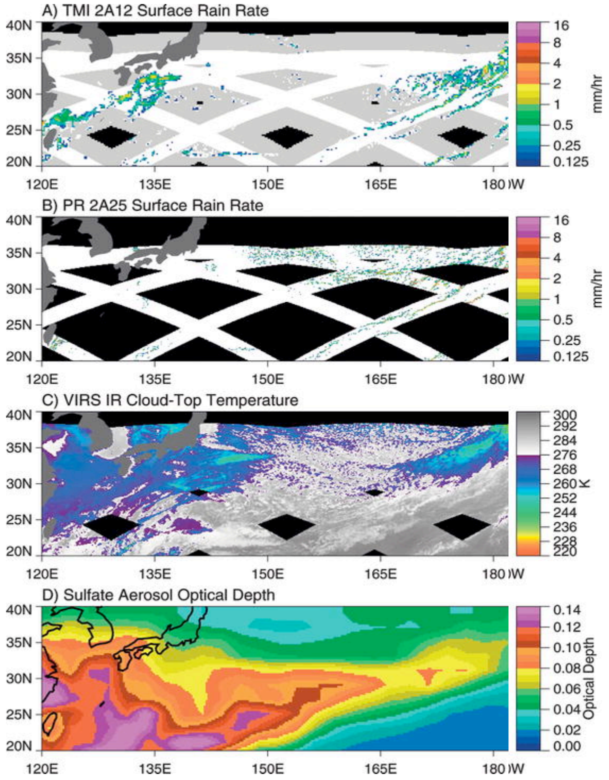

Fig. 9. (a) TMI 2A12 rainfall, (b) PR 2A25 rainfall, (c) VIRS cloud-top temperatures, and (d) model-derived sulfate aerosol optical depth for 1 Feb 2000. The nonraining portions of the TMI scan outside of the PR scan in (a) are gray; nonraining TMI pixels within the PR scan are white. (From Berg et al. 2006)

precipitation, other results indicate that under certain conditions, aerosols may invigorate convection, leading to more lightning and more intense rainfall rates (Andrea et al. 2004, Lin et al. 2006). Berg et al. (2006) found evidence suggesting that high concentrations of sulfate aerosols over the East China Sea may be responsible for large amounts of cloud water in the cloud systems there. These systems are being erroneously reported as rainfall by the TRMM TMI retrieval algorithm (Fig. 9) while the PR data show very little rain. The hypothesis is that the pollution from South China is affecting the precipitation off-shore through an increase of aerosols that favors keeping the liquid water in the form of cloud water by not letting small droplets grow to precipitation size. Further research (and additional data) are needed to better define these relations and even to detect possible changes in that region over the TRMM era due to increased industrial activity.

Deforestation has significant impacts on precipitation through the alteration of the land surface and the creation of thermally driven circulations (Chagnon and Bras 2005). Deforestation rates in Brazil and Africa can be several thousand square miles per year. Since deforestation tends to be greatest in developing nations that do not have the observing systems needed to monitor precipitation, extension of the 9-year TRMM precipitation record will be critical for monitoring impacts of deforestation in the Amazon and around the world.

Another area of research is the use of TRMM information to link urban dynamic effects on precipitation related to the urban heat island via enhanced roughness and convergence. Shepherd et al. (2002) explored the feasibility of using TRMM PR data to identify rainfall anomalies possibly associated with the urban environments of Atlanta, Dallas and other U.S. cities. Shepherd and Burian (2003) used PR data to confirm anomalies over and downwind of Houston, Texas. Shepherd (2005) demonstrated the use of the TRMM-based multi-satellite precipitation analysis to extend their work to additional major global urban centers. This urban impact work is also starting to include the effect of urban aerosols.

The benefits of an extended TRMM mission for assessing human impacts on precipitation would be: (1) a longer sample record to determine if observed land-surface change and aerosol signals truly reflect climate change processes or local weather variability; (2) continued access to the TRMM precipitation radar, which is critical for direct measurement of precipitation in aerosol-laden, deforested, or urban environments rather than less direct techniques; (3) continued access to the unique combination of instruments on TRMM that allow for integrated land-surface-change/aerosol/precipitation studies to test emerging hypotheses; and (4) optimization of the TRMM-based MPA product to extend urban research to mid-latitude cities.

TRMM will provide an improved assessment of the impact of humans by increased air pollution, deforestation, and expansion of urban areas on climate change in the water cycle.

3.9 TRMM combined with new, unique observations

Science Question 15: What fraction of tropical precipitation occurs at rainrates below 0.5 mm/hr (PR threshold), and how does that fraction vary in space and time? [based on combination of TRMM PR and CloudSat radar data]

Science Question 16: How do microphysical (cloud, aerosol, precipitation) processes interact with mesoscale and larger dynamics in the initiation and evolution of tropical cyclones? [based on combination of TRMM and MODIS data]

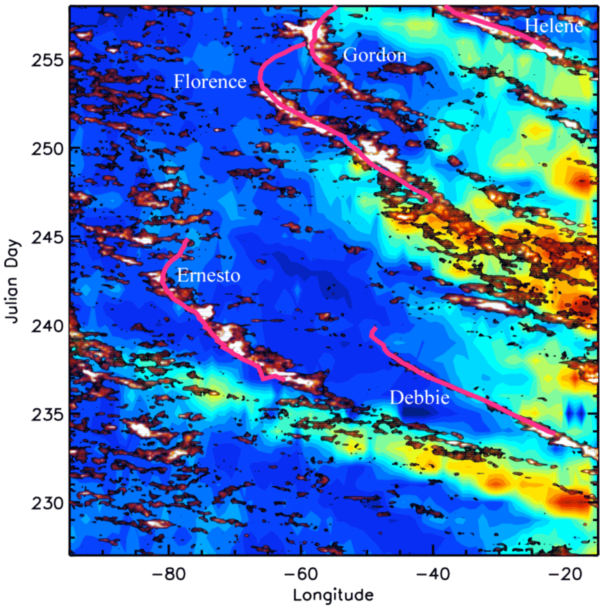

Fig. 10. Longitude-time plots of daily MODIS aerosol optical depth (blue-to-red shading), 3-h TMPA rain rate (black-orange-white shading) and hurricane tracks (red lines) from Aug. 15 to Sept. 15, 2006, corresponding to the NAMMA field program. The TMPA and MODIS data are averaged over the latitudinal band between 7.5 and 27.5°N.

Science Question 17: How does lightning frequency and distribution, and the associated variation in precipitation processes, affect the production, distribution, and variation of NO_x? [based on combination of TRMM and Aura data]

Extending TRMM for the next few years will allow for unique overlap with data sets that will be highly useful in pursuing new science questions and adding to existing research endeavors.

The most obvious example of such a contribution is the combination of information from CloudSat (and the entire "A-Train") and TRMM. CloudSat uses radar (95 GHz) to measure the vertical structure of clouds from space including some characteristics of precipitation. CloudSat flies in formation with other satellites (including Aqua) collectively referred to as the "A-Train." This constellation came into formation with the launch of CloudSat and CALIPSO (with its cloud lidar) in mid-2006. Combining the observations of the A-Train with TRMM will provide an unprecedented view of clouds, aerosol, and precipitation. Because the TRMM and CloudSat mission satellites both carry radars, but with different and complementary wavelengths, the opportunity to have measurements at both radar frequencies simultaneously over a substantial amount of time will provide a basis for statistical comparison and cross-referencing. 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 also important for GPM algorithm development, in particular through validation of algorithms for higher-latitude precipitation. GPM will provide radar information at 14 and 35 GHz. TRMM information (especially the radar) will also add value to the A-Train observations of clouds and precipitation, to the effects of pollution and aerosols on precipitation, and, in combination with water vapor observations from the Microwave Limb Sounder (MLS) on Aqua, to examine the role of detraining deep tropical convection in moistening the Tropopause Transition Layer.

The large-scale environment exerts a significant influence on the development and evolution of hurricanes. For example, recent studies have suggested a large influence of the Saharan Dust Layer on the ability of hurricanes to form and intensify in the Atlantic, with some (Karyampudi and Carlson 1988, Karyampudi et al. 1999) suggesting a possible positive influence and others a negative influence (Dunion and Velden 2004). Rainfall from the TRMM MPA and aerosol optical depth data from MODIS on Terra and Aqua can be combined to examine the relationship between westward moving dust outbreaks from Africa and hurricane activity in the Atlantic (Fig. 10). Data from multiple years suggests that hurricanes often form either at the leading edge or just trailing major dust outbreaks and there is considerable variability from year to year. Unfortunately, MODIS data from both Terra and Aqua data are required to adequately resolve the daily evolution of the dust outbreaks, so the analysis is currently only available for 2002-2006. The TMPA data is critical for characterizing the evolution of the convective systems, so the development of an adequate multi-year climatology of the relationship between dust and hurricane rainfall requires the extension of TRMM and MODIS.

The atmospheric chemistry community has been one of the largest consumers of archived LIS data sets. Lightning heats a channel to tremendous temperatures and nitrogen oxides (NO_x) are produced. The NO_x eventually enhance tropospheric ozone concentrations through catalytic reactions provided other chemical species are present. It is estimated that almost all of the NO_x over the oceans and 50–90% of NO_x emitted over some continental areas on a seasonal basis is attributable to lightning (Bond et al. 2002). One of the science objectives for the Tropospheric Emission Spectrometer (TES) on Aura is to examine the production of NO_x from lightning. Continuation of TRMM will allow for linkage to key information provided by LIS.

As stated before, the combination of TRMM's TMI and PR with the microwave sensors on other current satellites provides many of the key elements of a GPM constellation concept. Data from the PR and TMI provide the rainfall reference point for the entire constellation thereby enhancing the data products from all constellation sensors. TMI has also served as a calibration standard for the other passive microwave sensors because of its excellent, steady calibration and its inclined orbit, which provides numerous crossovers with the polar orbiting sensors. In a similar way, the LIS provides calibration for the surface lightning networks, whose performance is affected by topography, conductivity, the state of the ionosphere, and other radio propagation effects.

Unique opportunities also exist for the TRMM mission to enhance atmospheric field campaigns over the next several years. In previous years, TRMM has provided key observations for hurricane related field programs such as CAMEX-3, CAMEX-4, TCSP, and NAMMA. TRMM will also provide critical information for the upcoming Tropical Composition, Cloud, and Climate Coupling (TC-4) field experiment in Costa Rica in the summer of 2007.

Continuation of TRMM will allow for new, unique joint data sets with Cloudsat, other satellites and field experiments to extend our knowledge of cloud, aerosol, precipitation and chemistry characteristics and interactions.

3.10 Applications and operational use of TRMM data

Science Question 18: What is the impact of TRMM data in the forecasting of position and intensity of tropical cyclones, and how does that vary with type of storm, ocean basin, etc.?

Science Question 19: What are the quantitative limitations for various applications of the accuracy and the time and space resolutions available from space observations of precipitation?

As indicated in section 2.5 of this document and confirmed by the NA conclusion on operational applications (see section 2.6), TRMM data have been effectively used in various applications over the past nine years and clearly these uses will be continued and improved, while new applications will be developed. In tropical cyclone monitoring and forecasting, TRMM TMI will continue to provide ~600 location fixes per year at different times than available from polar-orbiting passive microwave instruments. PR data are available in real-time (same latency as TMI). In 2005, Goddard scientists, with advice from NRL and NHC personnel, developed a real-time PR/TMI tropical cyclone product that is now available for forecasters (see example in Fig. 11). It shows PR surface rainfall rates at full resolution (5 km) with TMI rainrates in the wider part of the swath to provide larger-scale information and context. Three-dimensional structure from the PR data over the storm is also displayed for evaluation of radar echo strength, height, etc. Since accuracy of initial locations affects model forecasts of position, it can be assumed that TRMM observations of initial position are positively impacting forecasts. Models will also make improvements in assimilation of precipitation information for forecast improvement, so TRMM's impact should increase even beyond what has already been shown.

In addition, extension of TRMM will allow for the PR to be more widely used to calibrate ground-based radars (Bolen and Chandrasekar 2003, Anagnostou et al. 2001), which will improve surface-based rainfall estimates in the U.S. and abroad.

Operational data products using TRMM data as the keystone in techniques using multiple satellites to analyze precipitation at high time resolution will continue to improve. The utilization of these data sets for various practical applications such as flood detection and forecasting, landslide detection, aviation hazards, crop moisture monitoring, and soil moisture estimation will expand.

Continuation of TRMM will result in additional improvement in the monitoring and forecasting of tropical cyclones, floods and other hazardous weather.

3.11 Flight operations, data processing and data products for the basic mission continuation

Leading up to the 2005 Senior Review, budgets related to TRMM flight operations, data processing and science were reduced as TRMM went into the extended portion of its mission. For the upcoming 2008-2012 period, the requirements for the basic mission extension remain the same as for the 2006-2007 period. A 55-member U.S. Precipitation Measurement Missions (PMM) science team has recently (late 2006) been selected through ROSES to carry out research with

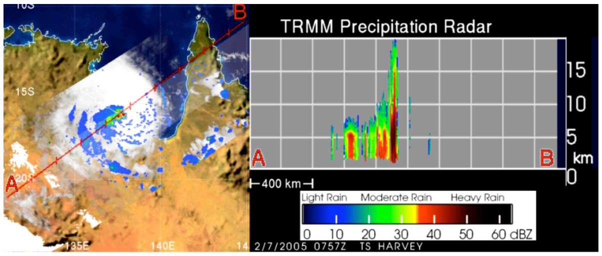

Fig. 11. Example of prototype real-time PR product for tropical cyclone monitoring and research. Example is for Tropical Cyclone Harvey in northern Australia in February 2005.

TRMM data and prepare for GPM. JAXA-sponsored TRMM research also continues in Japan. **In order to accomplish the ROSES-funded research and provide real-time TRMM products to operational agencies and the community, flight operations, data processing, and mission-related science support must continue at the proposed funding level for the basic mission continuation**.

The set of TRMM standard research products (see appendix for mission data product summary) will continue to be processed and sent to the Goddard DISC for archival and dissemination. In addition, the real-time versions of many of these same products will continue to be processed and made available directly from TSDIS. The real-time products, including products from the TRMM satellite alone and also the multi-satellite rain product, are produced in TSDIS separately from the standard (research) products and are used by numerous U.S. and international agencies and other entities.

Currently, the TRMM standard products are Version 6, with the reprocessing based on that version of the algorithms being completed in 2005. PMM science team members are continuing to improve the algorithms and we are planning a reprocessing of the entire TRMM data set with a Version 7 of the algorithms to begin in 2008 and be completed in 2009. This new product data set is necessary to take advantage of knowledge gained by inter-comparison among the radar and passive microwave retrievals and ground validation information. Also, remaining effects on the retrievals related to the orbit boost in 2001 will be eliminated or reduced even further. Significant testing of proposed Version 7 algorithms will precede the operational reprocessing. This next version of the TRMM products is another step in the continuous effort for improved precipitation information from TRMM evolving toward and into GPM. TRMM and GPM (and their products) are linked.

The set of TRMM precipitation standard products is listed in the appendix. Multiple rain algorithms have been developed, inter-compared and used for analysis because of the difficulty of making this remote sensing observation, the strengths and weaknesses of the various approaches and the multiplicity of research applications. These different algorithm methodologies exploit different physical attributes of hydrometeors (scattering vs. emission, reflectivity vs. extinction, vertical structure). The availability of multiple techniques aids in understanding and verification and has led to significant advances in the remote estimation of precipitation. The multi-satellite products utilize the TRMM information to calibrate, or adjust, the rain estimates from other, less capable instruments and then combine all the satellite estimates into multi-satellite analyses at high time resolution (~ 3 h). Brief descriptions of the standard TRMM algorithms are given in an Appendix. Real-time versions of 2A12, 2A25, and 3B42 are produced by TSDIS. In addition, a set of gridded products (3G68) (as opposed to pixel level) are produced for 2A12 and 2A25.

Enhanced Mission Section

4. PROJECT-LED ENHANCED SCIENCE DATA PRODUCTS

The continuation of the TRMM basic mission will continue to produce the TRMM standard research products and real-time versions of these products. An improved Version 7 of these products will replace the current Version 6 in 2008-2009. This level of data production is part of the TRMM basic mission extension as outlined in the previous section. However, the advances in science and in algorithm/product development have led to proposals for new TRMM products that can only be accomplished with additional resources through enhanced mission funding. The funding would primarily go to product development (outside of science team funding) and testing and product production in TSDIS. The following enhanced satellite and validation products will only occur under enhanced funding.

4.1 Precipitation Feature (PF) database

PMM science team members (University of Utah) and other scientists have developed a precipitation feature (PF) database originally defined by Nesbitt et al. (2000). Starting with this definition, the global distribution of storms with LIS-detected lightning (Cecil et al. 2005), deep convection reaching the tropical tropopause layer (Liu and Zipser 2005), rainfall production and convective organization (Nesbitt et al. 2006), and extreme thunderstorms (Zipser et al. 2006) have been studied. In 2006, there was a major improvement to the database by using a full set of new definitions. The current database is constructed with three levels of processing of the TRMM data (see description and table below). It consists of over 20 million individual precipitation features over a 9-year period. **As part of the TRMM enhanced mission, the goal would be to implement the PF database as a standard TRMM product in TSDIS (it already runs in TSDIS as an experimental product) and deliver data sets to the Goddard DISC for community distribution.** This product is being increasingly used in the research community and making it standard and a part of the overall TRMM database would enhance research in this area.

Table 4. Definition of precipitation feature and cold cloud features in PF database.

Definition	Criteria
Radar detected Precipitation Feature (RPFs)	Pixel with 2A25 rainfall rate >0
Microwave imager detected Precipitation Feature inside PR swath (MPFPs)	Pixels with 2A12 rainfall rate > 0 inside PR swath
Microwave imager detected Precipitation Feature inside TMI swath (MPFTs)	Pixels with 2A12 rainfall rate > 0
Microwave image cold 85 GHZ PCT feature inside PR swath (CBTFs)	Pixels with 85 GHZ PCT < 250 K
Very Cold Cloud Features (VCCFs)	VIRS $T_{B11} < 210$ K inside PR swath
Cold Cloud Features (CCFs)	VIRS $T_{B11} < 235$ K inside PR swath

The basic structure of the product is as follows:

- Using level-1 TRMM data and the definition of features in Table 4, RPFs, MPFs, MPFTs, MPFPs, VCCFs, and CCFs are grouped. The statistics, such as volumetric rain, flash counts, and maximum height of 20 dBZ etc., for each RPFs, MPFs, MPFTs, MPFPs, VCCFs, and CCF are derived. Then, collocations with NCEP reanalysis (Kistler et al., 2001) parameters and monthly combination of orbital data are performed to obtain the level-2 feature data.

There are a total of 166 and 68 variables from level 2 and 3 products respectively. Some representative quantities are:

a. Level 2
  - Area, 2A12 surface rain rate, 2A25 surface rain rate, minimum 37 and 85 PCT of each feature
  - Maximum height of 20, 30, 40 dBZ, maximum reflectivity at 6, 9 km of each feature
  - Minimum 10.7 μm T_b, flash counts, surface PR reflectivity of each feature
  - Area of 20 dBZ at 6 km, 10k, and 14 km in features
  - Area of 2A25 rain, 2A12 rain, 10.7 μm $T_b < 210$ K, 235 K in each feature
  - PF center temperature, wind, relative humidity profiles, tropopause height

b. Level 3
  - Monthly rain estimate from GPI, GPCP, GPCC, TRMM 3A25, 3B43
  - Mean rain rate of RPFs, RPFs with ice, without ice and MCSs defined from RPFs
  - Total number, mean area, mean volumetric rain, stratiform ratio of RPFs, MPFs, MPFTs, MPFPs, VCCFs, and CCFs.
  - Mean and minimum 37 and 85 GHz PCT of different types of features.
  - Mean and minimum 20, 30, 40 dBZ height of different types of features.
  - Flash counts and total numbers with flashes of different types of features.

4.2 Wide-swath primary precipitation product

Currently, TRMM has three instantaneous orbital swath precipitation products: 2A12 using TMI, 2A25 using PR and 2B31 using a combination of TMI and PR. Because the swath width of the PR is narrower than TMI, the products that use PR are limited to that relatively narrow swath. Although the differences between the precipitation products have narrowed as the different versions of the products have evolved, there is still is a need to continue the individual products to understand the physical basis for the differences. This will lead to further improvements in TRMM-based information, in information from other satellite passive microwave retrievals, and eventually for GPM. However, the user community is often confused as to which TRMM product to use for both instantaneous estimates and for time-space averaging and climate diagnostics. It is clear that the PR information provides a strong basis for rain estimates and should be used wherever possible. However, that limits you to the narrow swath, and users who require a wider view on an instantaneous basis or better sampling on a time-averaged basis tend to use the products that use only the TMI passive microwave data. What is needed is a merged swath product that uses the PR information where available in the inner swath (either alone or more likely combined with TMI data) and uses the TMI-based product in the outer swath in a way that produces a complementary product. The result will be a TRMM best estimate of precipitation across the wide swath. This will probably require a procedure where the inner swath, higher quality estimates are used to calibrate the passive microwave estimates in the outer swath in order to provide a seamless estimate across the swath. TRMM researchers are already developing this type of approach. The first version of this product might be surface precipitation only, but vertical hydrometeor structure could be included, probably in following versions of the product.

4.3 TRMM sub-sets for matching A-Train data

The A-Train data sets of Aqua, Cloudsat and CALIPSO are being used by the research community to examine many characteristics of aerosols, clouds and precipitation using both the active and passive observations from optical to microwave wavelengths. Although TRMM is in a very different orbit, there are already a number of crossover matches between TRMM and the A-Train. The number of these overlapping data sets will increase as both the TRMM and the A-Train missions continue over the next four or more years. This new product will subset TRMM data (level 1 and 2 standard products from PR, TMI, VIRS and LIS) for a small portion of the TRMM orbit within a set of time intervals, Δt, of orbit cross-over points. This subsetting of TRMM data sets will be done for more than one Δt in order to satisfy requirements of various investigators. A likely set of Δt's will be 1 min., 5 min., 30 min. and 1 hour. Having data sets that add TRMM data to the A-Train mix will allow for comparison with the 14 GHz PR data at 250 m vertical resolution with Cloudsat and CALIPSO vertical profiles. LIS data will add electrification information to the total data set. TRMM and Aqua share two types of instruments that will allow for evaluation of the validity of data match-ups. In the microwave area, TRMM has TMI and Aqua has AMSR, with a number of similar or identical frequencies. In the IR part of the spectrum, TRMM has VIRS and Aqua has MODIS. These subsets of TRMM data will be made available to the Goddard DISC so that investigators can easily add TRMM's unique observations to those of the A-Train with minimal effort. TRMM subsets for overlaps for the five-year period of Aqua and TRMM overlap will be calculated in a re-processing mode and then produced on a month-by-month basis into the future.

4.4 Tropical cyclone rain accumulation maps

The TRMM multi-satellite precipitation product (TMPA) provides rain rate information every 3 h at 0.25° spatial resolution. By using information on the tracks of hurricanes (latitude and longitude information available every 3-6 h), the TMPA rain rates can be used to compute the total rainfall accumulation associated with hurricanes and time series reflecting changes in either the radial or azimuthal precipitation structure. Changes in the radial structure may highlight changes in storm intensity and expansion or contraction of the rain area, while changes in the azimuthal asymmetry of a storm (whether precipitation is uniform about the center or favored on one side) may indicate the influence of environmental wind shear. These products are obtained by interpolating the rainfall data onto a polar grid system centered on the observed storm center position. The rainfall accumulation is obtained by summing the rainfall within 6° of center (to exclude rainfall from other nearby, in time or space, systems) at each TMPA analysis time over the life cycle of an individual storm. The radial-structure time series plot is obtained by averaging the rainfall around the storm for each radius while the azimuthal-structure time series is obtained by averaging over the inner radii out to 1° from the center for all directions about the center. Prototype products are currently available from the TRMM web page for storms between 1998-2005. Here, we propose to produce similar products in near real time using the 3B42-RT rainfall product.

5. BUDGET

Over the last few years, TRMM science, flight operations, and data processing budgets have been reduced as TRMM moved into extended mission phase. Mission flight operations support is now through Capitol College, allowing for student involvement and significant cost savings. At the same time, the ground system has been replaced by a more automated system, which is being used as a prototype for other missions (e.g., Terra, Aqua and Aura). Science data processing (TSDIS) operations have also been streamlined over the same period with significant cost savings. Over the next few years as TRMM continues, the new processing system (PPS) will be developing (under separate budget) to support GPM and the overall Precipitation Program. A transition will occur where PPS will be used to produce all TRMM products. For example, TRMM Version 7 products may also be designed to be Version 0 of GPM, produced with the PPS system, and run on TRMM-funded computers. Version 7 processing is planned to start in 2008. This transition from TSDIS to PPS will allow for efficient continuation of production of precipitation products going from TRMM to GPM in a cost effective manner.

Since 2003, TRMM no longer has a separate science team. Instead, **TRMM-related science is accomplished under the ROSES-funded Precipitation Measurement Missions (PMM) Science Team**, which combines science activities related to TRMM and the forthcoming GPM mission. During the next four years, there will be a continuous shift toward GPM-related activity. **Although total PMM mission-directed science funding (non-ROSES) is expected to remain about constant, the TRMM portion of that funding will decrease from the current year through the 2008-11 period (see budget sheets in Appendix B). The flight operations and satellite data processing (TSDIS) funding are requested to remain constant during the proposal period.** The modest additional funds necessary for the enhanced mission (enhanced products described in Section 4) are also detailed in Appendix B, and involve resources for developing and testing the proposed new products and in implementing and producing the products in TSDIS. Budgets for LIS operations, data processing and science through MSFC are carried in the following budgets as separate lines because LIS is an EOS instrument and is funded separately from TRMM and the Precipitation Program.

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Appendix A: TRMM Mission Data Product Summary

All TRMM products start from Dec. 1997 (duration is 9+ years); TRMM standard products (non real-time) are used by researchers in many U.S. and foreign agencies and universities; real-time TRMM products are used by various U.S. and foreign agencies and universities for operational applications. In the following table, a detailed list of users is given only for the real-time TRMM products.

Level 1Standard Satellite Products

Name	Product No.	Instrument	Product Description	Users	Access
VIRS Radiances	1B01	VIRS	Geolocated and calibrated radiances for all infrared and visible channels. At the instrument field of view.		GSFC/DISC
TMI Brightness Temperatures	1B11	TMI	Geolocated and calibrated brightness temperatures in 7 low resolution and 2 high resolution channels. At the instrument field of view.		GSFC/DISC
PR Received Power	1B21	PR	PR received power for 49 angle bins. Calibrated and geolocated. Includes normal sample, surface oversample and rain oversample powers. At the instrument field of view.		GSFC/DISC
PR Reflectivities	1C21	PR	PR reflectivies for 49 angle bins. Calibrated and geolocated. Includes normal sample, surface oversample and rain oversample reflectivities. At the instrument field of view.		GSFC/DISC
LIS Radiances	1B	LIS	Background images and science data at the instrument field of view. Backgrounds are snapshots of the near-IR LIS field-of-view saved ~ every 90 sec. Each file contains 1 orbit of data.		MSFC/GHRC

*Level 1**Real-time** Satellite Products*

Name	Product No.	Instrument	Product Description	Users	Access
VIRS Radiances	1B01rt	VIRS	Basically the same as the 1B01 VIRS product in production but uses predictive rather than definitive ephemeris. Geolocation is 2 byte integer for lat and for long rather than 4 byte as in production.		GSFC/DISC
TMI Brightness Temperatures	1B11rt	TMI	Reduced 1B11 production quick look algorithm that includes only brightness temperatures and geolocation information. Uses predicitive ephemeris rather than definitive. Geolocation is 2 byte integer for lat and for long rather than 4 byte as in production.	NOAA (NCEP) DOD (NRL) ECMWF JMA	GSFC/DISC
LIS Flashes	1B	LIS	Ascii text files containing latitude, longitude, and radiance for each flash in each orbit. Uses predictive ephemeris.	NCEP	MSFC/GHRC

PR 20 level profiles	1C21rt		PR reflectivities at 20 vertical levels. A reduced parameter product based on the production 1C21 algorithm that provides rain profiles at 20 vertical levels rather than at 80 as in the production product.	NRL	GSFC/DISC

Level 2 Standard Satellite Products

Name	Product No.	Instrument	Product Description	Users	Access
Surface cross section	2A21	PR	Radar surface scattering cross section/total path attenuation.		GSFC/DISC
PR rain type	2A23	PR	Type of rain (convective/stratiform) and height of bright band.		GSFC/DISC
TMI profiles	2A12	TMI	Surface rainfall and 3D structure of hydrometeors and heating over TMI swath.		GSFC/DISC
PR profiles	2A25	PR	Surface rainfall and 3D structure of hydrometeors over PR swath.		GSFC/DISC
PR-TMI profiles	2B31	PR, TMI	Surface rainfall, hydrometeor structure and heating.		GSFC/DISC
LIS	Level 2	LIS	LIS events (individual optical pulses produced by lightning flashes), groups, flashes, areas, and viewtime.		MSFC/GHRC

*Level 2 **Real-time** Satellite Products*

Name	Product No.	Instrument	Product Description	Users	Access
TMI surface rain	2A12rt	TMI	Based on production product but provides surface rain parameters only. No vertical information included. Uses predicitive ephemeris rather than definitive.Geolocation is 2 byte integer for lat and for long rather than 4 byte as in production.	NOAA NCEP JMA ECMWF NRL	TSDIS
PR rain type	2A23rt	PR	A reduced parameter product based on the production 2A23 algorithm. The realtime product includes only geolocation, rain type, storm height and freezing height parameters. Uses predicitive ephemeris rather than definitive.Geolocation is 2 byte integer for lat and for long rather than 4 byte as in production.		TSDIS
PR surface rain	2A25rt	PR	A reduced parameter product based on the production 2A25 algorithm that provides estimated surface rain, and near-surface reflectivity.	NOAA NCEP JMA ECMWF NRL	TSDIS
PR 20 level profiles	2A25rt	PR	PR rain retrieval at 20 vertical levels. A reduced parameter product based on the production 2A25 algorithm that provides rain profiles at 20 vertical levels rather than at 80 as in the production product.	NRL	TSDIS

Level 3 Satellite Standard Products

Name	Product No.	Instrument	Product Description	Users	Access
TMI monthly rain	3A11	TMI	Monthly 5^{o} rainfall maps-ocean only.		GSFC/DISC
PR monthly average	3A25	PR	Monthly 5 ^{o} rainfall and structure statistics from PR.		GSFC/DISC
PR-TMI monthly average	3B31	PR, TMI	Monthly accumulation of 2B31 products and ratio of this product with accumulation of 2A12 in overlap region.		GSFC/DISC
TMI, PR, Combined swath rain gridded	3G68	TMI, PR	Daily product containing hourly surface rain from TMI, PR, and combined. .5 x .5 degree resolution. In text format.		TSDIS
TMI, PR, Combined swath rain gridded	3G68 Land	TMI, PR	Daily product containing hourly surface rain from TMI, PR, and combined. .1 x .1 degree resolution. In text format for Australia, Africa, and South America.		TSDIS
TRMM Multi-satellite (3-hr)	3B42	PR, TMI AMSR SSM/I AMSU GEO-IR	Multi-satellite (TRMM, AMSR, SSM/I, AMSU, Geo-IR) precipitation data calibrated by TRMM PR/TMI (Combined), 3-hourly, 0.25 ^{o} resolution.		GSFC/DISC
TRMM Multi-satellite/gauge (monthly)	3B43	PR, TMI AMSR SSM/I AMSU GEO-IR	3B-42 and gauge products-data merged into single rain product, monthly, 0.25^{o} resolution.		GSFC/DISC
LIS Browse	Level 3	LIS	Daily browse images showing ascending and descending orbits, locations of lightning, and statistical information.		MSFC/GHRC
LIS/OTD 0.5 Deg High Resolution Full Climatology	HFRC	LIS, OTD	0.5 Degree resolution composite of total lightning expressed as a flash rate density (fl km^{-2} yr^{-1}). Contains 5-yr OTD and 8-yr LIS and supporting base data (flash counts and view times). Detection efficiency and instrument cross-normalizations are applied. Annualized gridded composite of lightning data over the entire missions.		MSFC/GHRC
LIS/OTD 2.5 Deg Low Resolution Annual Climatology	LRAC	LIS, OTD	2.5 Deg resolution daily gridded composite of lightning data.		MSFC/GHRC
LIS/OTD 2.5 Deg Low Resolution Diurnal Climatology	LRDC	LIS, OTD	2.5 Deg resolution hourly gridded composite of lightning data.		MSFC/GHRC
LIS/OTD 2.5 Deg Low Resolution Full Climatology	LRFC	LIS, OTD	2.5 Deg resolution gridded annualized composite of lightning activity over the entire missions.		MSFC/GHRC

LIS/OTD 2.5 Deg Low Resolution Time Series	LRTS	LIS, OTD	2.5 Deg resolution gridded daily composite of lightning activity for each day of the OTD and LIS missions.		MSFC/GHRC
LIS/OTD 2.5 Deg Low Resolution Annual Climatology Time Series	LRACTS	LIS, OTD	2.5 Deg resolution gridded daily time series of lightning activity over a composite year.		MSFC/GHRC
LIS/OTD 0.5 Deg High Resolution Monthly Climatology	HRMC	LIS, OTD	0.5 Deg resolution gridded monthly and seasonal composites of lightning activity.		MSFC/GHRC
LIS/OTD 0.5 Deg High Resolution Annual Climatology	HRAC	LIS, OTD	0.5 Deg resolution daily grid of lightning activity over a composite year.		MSFC/GHRC
LIS/OTD 2.5 Deg Low Resolution Annual Diurnal Climatology	LRADC	LIS, OTD	2.5 Deg resolution hourly grids of lightning activity for each day of a composite year.		MSFC/GHRC
LIS/OTD 2.5 Deg Low Resolution Monthly Time Series	LRMTS	LIS, OTD	2.5 Deg resolution monthly grids of lightning activity for each month of the OTD and LIS missions.		MSFC/GHRC

Level 3 ***Real-time*** *Satellite Products*

Name	Product No.	Instrument	Product Description	Users	Access
Merged Multi-radiometer precipitation	3B40rt	PR, TMI AMSR SSM/I AMSU GEO-IR	Multi-satellite radiometer precipitation data calibrated by TMI, 3-hourly, 0.25° resolution.		TSDIS
IR precipitation	3B41rt	PR, TMI AMSR SSM/I AMSU GEO-IR	3-hourly IR precipitation data adjusted by radiometer data at 0.25° resolution.		TSDIS
TRMM Multi-satellite	3B42rt	PR, TMI AMSR SSM/I AMSU GEO-IR	Merged multi-satellite radiometer and radiometer adjusted IR precipitation data, 3 hourly, 0.25° resolution	NOAA NRL JMA USGS	TSDIS

TRMM Ground Validation Products

Name	Product No.	Instrument	Product Description	Users	Access
Surface radar Reflectivity (DZ), Doppler velocity (VR), ZDR	1B-51	Ground Radar	Original coordinates and fields. Maximum range 230 km.		GSFC/DISC
Quality-controlled reflectivity (CZ), DZ, VR	1C-51	Ground Radar	Original coordinates. CZ contains quality-controlled DZ field, Maximum range 200 km. HDF format.		GSFC/DISC
Echo Coverage	2A-52	Ground Radar	Percentage echo coverage with satellite coincidence. ASCII format.		GSFC/DISC
Rain Intensity	2A-53	Ground Radar, Rain gauge	Cartesian grid (2 km x 2 km, 151 x 151 pixels). Instantaneous rain intensity (mm hr-1). Maximum range 150 km. HDF format.		GSFC/DISC
Rain Type	2A-53	Ground Radar, Rain gauge	Cartesian grid (2 km x 2 km, 151 x 151 pixels). Rain type (stratiform or convective). Ground radar, raingauge Maximum range 150 km. HDF format. From Steiner et al. (1995)		GSFC/DISC
Quality-controlled reflectivity (CZ) gridded	2A-55	Ground Radar, Rain gauge	3-dimensional Cartesian Grid (2 km x 2 km horizontal, 1.5 km vertical; 151 x 151 x 13 pixels). Quality-controlled reflectivity. Maximum range 150 km. Maximum height 19.5 km. HDF format.		GSFC/DISC
Rain rate (1-minute)	2A-56	Ground Radar, Rain gauge	1-minute average gauge rain rates. One file per month, per gauge. ASCII format.		GSFC/DISC
Rain rate (5-day)	3A-53	Ground Radar, Rain gauge	Cartesian grid (2 km x 2 km). Five-day integrated rainfall. Maximum range 150 km. HDF format.		GSFC/DISC
Rain rate (monthly)	3A-54	Ground Radar, Rain gauge	Cartesian grid (2 km x 2 km). Monthly-integrated rainfall. Maximum range 150 km. HDF format.		GSFC/DISC

TRMM Enhanced Mission Satellite Products (Proposed)

Name	Product No.	Instrument	Product Description	Users	Access
Precipitation Feature (PF)	E-PF Levels 1,2,3	PR, TMI, LIS, VIRS	Feature locations and characteristics as described in Sec. 4 text		GSFC/DISC
Wide-swath Precipitation	E-WSP Levels 2,3	PR, TMI	Surface precipitation estimates at swath locations and monthly totals		GSFC/DISC
A-Train Subsets	E-Atrain Levels 1,2	PR, TMI, VIRS, LIS	Subsets of all Level 1 and 2 TRMM products for A-Train intersections within indicated time offsets		GSFC/DISC
Tropical Cyclone Rain Maps	E-TCR Level 3	TRMM+ other satellites (3B42)	Gridded rain totals for tropical cyclones identified by storm tracks		GSFC/DISC

Description of Primary TRMM Standard Rain Algorithms/Products

TMI Surface Rain and Profiling Algorithm - (2A-12): The TMI profiling algorithm (often referred to as GPROF [Goddard Profiling]) makes use of the Bayesian methodology to relate the observed multi-channel brightness temperatures to the hydrometeors provided in an a-priori database. This initial database is supplied by non-hydrostatic cumulus-scale cloud models using explicit cloud microphysics. By taking a large number of simulations and a number of time steps within each simulation, a fairly robust set of possible cloud realizations is created. Radiative transfer computations are then used to compute brightness temperatures (T_b). These T_b are finally convolved with the known antenna patterns of the TMI to generate the corresponding T_b the satellite would observe. In the Bayesian approach, the RMS difference between observed and modeled T_b are used to assign weight to each cloud model profile in the a-priori database to derive new composite profile. The basic technique is described in more detail in (Kummerow et al. 1996, 2001).

The output product from 2A-12 consists of the surface rainfall rate, convective rain fraction, and a confidence parameter, as well as the 3-D structure and latent heating using 14 vertical layers. There are four hydrometeor classes (rainwater, cloud water, precipitation-size ice, and cloud ice). While the structure information may not be as detailed as that which can be obtained from the PR instrument, the much wider swath of the TMI makes this product important for climatological purposes. Over land, where the emission signature of rain water cannot be detected directly, a semi-empirical relation based upon climatological rainfall derived from the TRMM PR and ground measurements is used.

PR Surface Rain and Profiling Algorithm - (2A-25): The primary objective of 2A-25 is to produce the best estimate of the vertical rainfall rate profile for each radar beam from the TRMM PR data. The 2A25 algorithm retrieves the precipitation profiles in two steps. It estimates the true effective reflectivity factor (*Ze*) from the measured vertical profiles of reflectivity factor (*Zm*) first, and then converts the estimated *Ze* into the rainfall rate (*R*). The step to estimate *Ze* from *Zm*, which corresponds to the attenuation correction, is carried out by using a hybrid method described in Iguchi and Meneghini (1994). The path-integrated attenuation (PIA) is estimated in such a way that it conforms to the PIAs from both the surface reference technique (2A-21) and the Hitschfeld-Bordan method when the relative accuracy of the methods is taken into account in a given circumstance. The estimated *Ze* is then converted into *R* by using an appropriate *Ze-R* relationship, which is adjusted according to the rain type, the altitude, and the correction factor used in the hybrid method of attenuation correction. Both the attenuation corrected *Ze* and the rainfall rate estimate *R* are given at each resolution cell (4 km × 4 km × 250 m) of the PR.

Combined PR/TMI Surface Rain and Profiling Algorithm (2B-31): The guiding principle in the design of the combined algorithm was to merge information from the two sensors into a single retrieval that embodied the strengths of each sensor. The algorithm uses all the channels of the TMI to compare the candidate rain profiles, retrieved from the radar using different drop size distribution (DSD) assumptions, and quantify how consistent their radiances would be with the measured brightness temperatures. The output product consists of the surface rainfall rate as well as the 3-D structure and latent heating using 14 vertical layers.

A parameterization of the drop size distribution (DSD) using three mutually independent parameters is used. These are a) a quantity parameter R (the rain rate), and the two shape parameters D' and s', the first proportional to the mass-weighted mean drop diameter and the second proportional to the relative standard deviation of diameters about this mean. This parameterization produces *Z-R* and *k-R* relationships, which are indexed by the shape parameters. Within a given TMI footprint, one has multiple profiles of measured radar reflectivities. For twelve different settings of the shape parameters *Z* is inverted into a rain profile R. Parameterized forward radiative transfer formulas are used to derive the radiance that one would expect each rain profile to produce. These radiances are combined according to the position of the radar beam within the TMI footprint to synthesize the brightness temperature T that one would expect. The latter is then compared to the measured brightness temperatures T_b, and a weight w is derived to be used in averaging the rain rates corresponding to the different possible shape parameters . It is assumed that the DSD shape parameters are uniform in altitude and within the radar beam (Haddad et al. 1997).

Monthly Statistical TMI Surface Rain Algorithm (3A-11): The 3A11 algorithm produces monthly oceanic rainfall accumulations and other rain rate parameters on a 5° x 5° grid. It is used in addition to monthly accumulations of the instantaneous (level 2) algorithms. The algorithm, originally developed for SSM/I, is a statistical/physical algorithm that corrects for the monthly sampling and beamfilling biases (Wilheit et al. 1991, Chang and Chiu 1998). It is based on a rain rate-Tb relation derived from an atmospheric model that is completely specified by the rain intensity and the height of the zero degree isotherm (freezing height). The freezing height acts as a proxy of the integrated columnar water vapor. A combination channel of twice the 19 GHz minus the 21 GHz vertical polarization of TMI is used to minimize the effect of water vapor variability on the microwave rain signature. Monthly rain rates are modeled by a mixed log-normal distribution (Kedem et al. 1990). Monthly histograms of TMI and the combination channel Tbs are computed and fitted to a mixed log-normal rain rate distribution via the rain rate-Tb relation to correct for inadequate sampling. To account for the beam-filling error, the derived TMI rain-rate indices are then multiplied by a correction factor that is dependent on rain rate variability and the freezing height (Chiu et al. 1990, Wang, 1995). The functional dependence of the beamfilling correction on freezing height is based on model simulation using airborne radar observations.

Multi-satellite Surface Rain Algorithms (3B-42, 3B-43): Multi-satellite algorithms have been part of the TRMM set of standard algorithms since launch. Originally, the multi-satellite algorithm used TRMM information (the combined PR/TMI 2B-31 algorithm) to calibrate rain estimates from geosynchronous IR observations (Adler et al. 2000). In the current Version 6 processing the 3B-42 algorithm is the TRMM-based Multi-satellite Precipitation Analysis (MPA) (Huffman et al. 2003). The MPA is a quasi-global precipitation analysis at fine time and space scales (3-hr, 0.25° × 0.25° latitude–longitude) over the latitude band 50°N-S. This analysis scheme makes use of TRMM's highest quality, but infrequent observations, along with high quality passive microwave-based rain estimates from 3-7 polar-orbiting satellites, and even estimates based on the five geosynchronous IR data covering the tropics. The combined quasi-global rain map at 3-hr resolution is produced by using TRMM-based estimates (algorithm 2B-31) to calibrate, or adjust, the estimates from all the other satellites, and then combining all the estimates into the MPA final analysis. The technique uses as much microwave data as possible, including data from Aqua/AMSR and SSM/I's and AMSU's on operational satellites, and only uses the geo-IR estimates to fill in remaining gaps in the three-hour analysis. The calibrations are computed using monthly accumulations of matched data to ensure stability. A standard monthly estimate (product 3B-43) is calculated by incorporating monthly gauge information over land to adjust the satellite estimates over land. When the Version 6 re-processing is finished 3B-42 will provide a 3-hr resolution surface rainfall product for the entire TRMM period (January 1998-present). A similar, real-time version of the 3-hr MPA merged product is available on the U.S. TRMM web site (trmm.gsfc.nasa.gov) a few hours after observation time.

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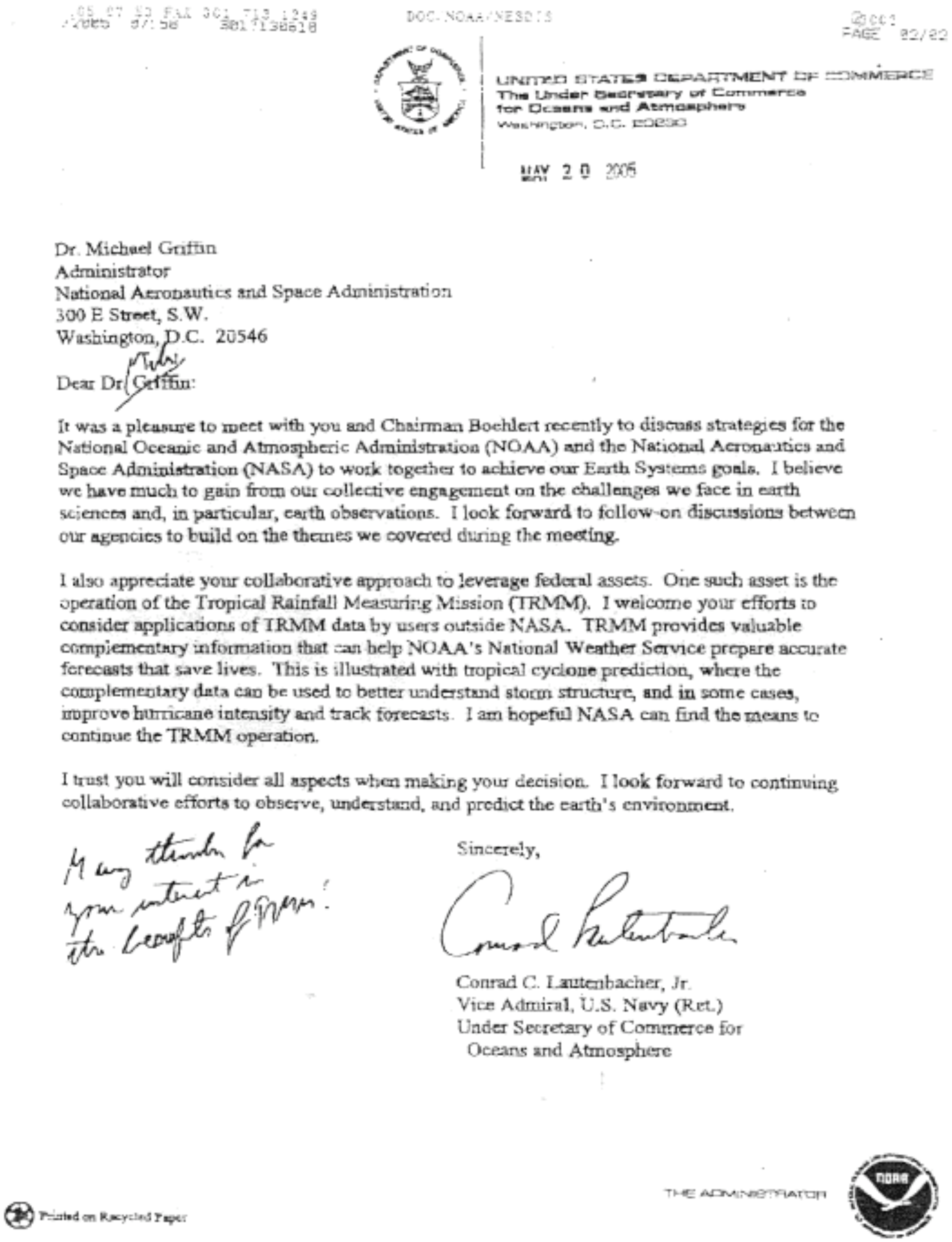
Appendix C – Acronyms

AESP	Aerospace Education Services Program
AIRS	Atmospheric Infrared Sounder
AMMA	African Multi-Disciplinary Monsoon Analysis
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
Aqua	Satellite of NASA's Earth Observing System (EOS), Latin for "water"
Aqua/AMSR	Satellite of NASA's Earth Observing System (EOS)/Advanced Microwave Scanning Radiometer
ARC	Active Radar Calibrator
ASTR	Along-track Scanning Radiometer
Aura	Satellite of NASA's Earth Observing System (EOS), Latin for "Air"
AVHRR	Advanced Very High Resolution Radiometer
AWC	Aviation Weather Center
C&DH	Command and Data Handling
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMEX	Convection and Moisture Experiment
CBTF	Microwave image Cold 85 GHz PCT Feature inside the PR swath
CCD	Charged-coupled device
CCF	Cold Cloud Features
CCSP	Climate Change Science Program
CERES	Clouds and Earth Radiant Energy System
CLIVAR	Climate Variability and Predictability Research
CloudSat	Cloud Satellite
CMAP	CPC Merged Analysis of Precipitation
CPC	Climate Prediction Center
DAAC	Distributed Active Archive Center
DISC	Data and Information Services Center
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DSD	Drop Size Distribution
DVAR	Dimensional Variation Assimilation System
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
EO	Earth Observatory
EOL	End of life
EOS	Earth Observing System
E/PO	Education and Public Outreach
ERBS	Earth Radiation Budget Satellite
ESMO	Earth Science Mission Operations
FSU	Florida State University
GDAS	Global Data Assimilation System
GES-DISC	Goddard Earth Science-Data and Information Services Center
GEWEX	Global Energy and Water Cycle Experiment
Giovanni	GES-DISC Interactive Online Visualization and ANalysis Infrastructure
GIS	Geographic Information System
GLDAS	Global Land Data Assimilation System
GPCC	Global Precipitation Climatology Center
GPCP	Global Precipitation Climatology Project
GPI	Global Precipitation Index
GPM	Global Precipitation Measurement

GSFC	Goddard Space Flight Center
GV	Ground Validation
ICE	Image Composite Editor
IFOV	Instantaneous field of view
IGES	Institute for Global Environmental Strategies
JAXA	Japan Aerospace Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Center
LDAS	Land Data Assimilation System
LIS	Lightning Imaging Sensor
MCS	Mesoscale Convective System
MJO	Madden-Julian Oscillation
MLS	Microwave Limb Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	Multi-satellite Precipitation Analysis
MPF	Microwave Precipitation Feature
MPFP	Microwave imager detected Precipitation Feature inside PR swath
MPFT	Microwave imager detected Precipitation Feature inside TMI swath
MSFC	Marshall Space Flight Center
NA	National Academies
NAMMA	NASA African Monsoon Multidisciplinary Activities
NASA	National Aeronautics and Space Administration
NASA/NOAA/DOD	National Aeronautics and Space Administration/National Oceanic and Atmospheric Administration/Department of Defense
NCEP	National Centers of Environmental Prediction
NEO	NASA Earth Observations
NES	NASA Explorer Schools
NESDIS	National Environmental Satellite, Data, and Information Services
NHC	National Hurricane Center
NICT	National Institute of Information and Communication Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRL	Naval Research Laboratory
NWP	Numerical Weather Prediction
OCC	Operations Control Center
OTD	Optical Transient Detector
PCT	Polarization Corrected Temperature
PF	Precipitation Feature
PI	Principle Investigator
PMM	Precipitation Measurement Missions
PPS	Precipitation Processing System
PR	Precipitation Radar
PRF	Pulse Repetition Frequency
QC	Quality control
RF	Radio Frequency
ROSES	Research Opportunities in Space and Earth Sciences

RPF	Radar detected Precipitation Feature
SADA	Solar Array Drive Actuators
SDPF	Sensor Data Procession Facility
SIGMETs	Significant Meteorological Advisories
SN	Space Network
SOC	State of charge
SOS	Science On a Sphere
SSM/I	Special Sensor Microwave/Imager
SST	Sea-Surface Temperature
SVS	Scientific Visualization Studio
TC-4	Tropical Composition, Cloud, and Climate Coupling
TCSP	Tropical Cloud Systems and Processes
TDRSS	Tracking and Data Relay Satellite System
Terra	NASA’s Earth Observing System (EOS) flagship satellite, Latin for “Land”
TES	Tropospheric Emission Spectrometer
TEXMEX	Tropical Experiment in Mexico
THORPEX	The Observing-System Research and Predictability Experiment
T/R	Transmitter/Receiver
TraP	Tropical Rainfall Potential
TRMM	Tropical Rainfall Measuring Mission
TMI	TRMM Microwave Imager
TMPA	TRMM Multi-satellite Precipitation Analysis
TOVAS	TRMM Online Visualization and Analysis System
TSDIS	TRMM Science Data and Information System
UARS	Upper Atmosphere Research Satellite
USAID	U. S. Agency for International Development
USGCRP	U. S. Global Change Research Program
USGS	U. S. Geological Survey
VCCF	Very Cold Cloud Features
VIRS	Visible and Infrared Scanner
VR	Virtual recorders
WCRP	World Climate Research Program
WSC	White Sands Complex
WSGT	White Sands Ground Terminal



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UNITED STATES DEPARTMENT OF COMMERCE
The Under Secretary of Commerce
for Oceans and Atmosphere
Washington, D.C. 20230

MAY 2 0 2005

Dr. Michael Griffin
Administrator
National Aeronautics and Space Administration
300 E Street, S.W.
Washington, D.C. 20546

Dear ~~Dr. Griffin~~ Mike:

It was a pleasure to meet with you and Chairman Boehlert recently to discuss strategies for the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) to work together to achieve our Earth Systems goals. I believe we have much to gain from our collective engagement on the challenges we face in earth sciences and, in particular, earth observations. I look forward to follow-on discussions between our agencies to build on the themes we covered during the meeting.

I also appreciate your collaborative approach to leverage federal assets. One such asset is the operation of the Tropical Rainfall Measuring Mission (TRMM). I welcome your efforts to consider applications of TRMM data by users outside NASA. TRMM provides valuable complementary information that can help NOAA's National Weather Service prepare accurate forecasts that save lives. This is illustrated with tropical cyclone prediction, where the complementary data can be used to better understand storm structure, and in some cases, improve hurricane intensity and track forecasts. I am hopeful NASA can find the means to continue the TRMM operation.

I trust you will consider all aspects when making your decision. I look forward to continuing collaborative efforts to observe, understand, and predict the earth's environment.

Many thanks for
your interest in
the benefits of TRMM!

Sincerely,

Conrad Lautenbacher

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

THE ADMINISTRATOR

Printed on Recycled Paper

January 24, 2007

Dr. Mary Cleave
Associate Administrator
Science Mission Directorate
National Aeronautics and
Space Administration

Dear Dr. Cleave

It is my great pleasure to communicate with NASA in a timely manner, and I would like to express my heartfelt thanks for NASA's continuous understanding of and cooperation for our activities in the field of Earth observation.

I understand that the TRMM decision made in 2005 to extend its operation has been highly welcomed and much appreciated by Japanese TRMM user community.
I hear that the further extension of the TRMM operation is going to be decided according to the NASA's next Senior Review result, which is planned to be held in this spring.
I would like to make comments about the continuation of TRMM operation, on behalf of the Japanese user community.

More than 9 years of observation data have been accumulated since the TRMM launch.
The Japanese science community is pointing out the importance of the invaluable accumulated TRMM data set, and desiring the further accumulation of the data by continuing the TRMM observation.
In Japan, TRMM data are used not only by the science community but also by operational organizations.
Japan Meteorological Agency is using TRMM data in their daily numerical weather forecast.
The International Flood Network (IFnet), which is initiated by the Ministry of Land, Infrastructure and Transport Japan, is using TRMM data in their demonstration of real application of satellite data in flood forecasts.
These organizations want the continuation of TRMM observation vigorously.

The Precipitation Radar (PR) on TRMM has been working perfectly since the launch. Considering the robust design of the PR (active phased-array), we expect that it will continue to work well for the further extended operation period.

Japan Aerospace Exploration Agency
Marunouchi Kitaguchi Building, 1-6-5, Marunouchi, Chiyoda-ku, Tokyo 100-8260 Japan
Tel. 81 3-6266-6249 Fax. 81 3-6266-6908

In addition, the Council of Science and Technology Program (CSTP), which evaluates science and technology projects and makes the strategy of science and technology policy in Japan, has appraised the GPM program very positively. However, the following points were considered with respect to the delay of the GPM core observatory launch:

"Minimize the gap between TRMM and GPM by continuing the TRMM observation and satisfy the request of the user community. For the smooth transition from TRMM to GPM, carry out application studies and demonstrations with TRMM data and keep showing the importance and necessity of GPM vigorously."

Taking into account the great expectations in Japan for precipitation missions that includes TRMM and GPM, and considering its valuable contribution for GPM program promotion, we suggest that it is very worthwhile to continue TRMM observation, data dissemination, and science and application studies, together with NASA.

We look forward to working with you continuously on the remainder of TRMM's science mission life, and further on the future missions.

Sincerely yours,

Yasushi Horikawa
Executive Director

cc. Dr. Freilich, Director of Earth Science Division, SMD, NASA HQ
Dr. Adler, TRMM project scientist, GSFC, NASA

Education/Public Outreach Summary and Planned Activities
Senior Review 2007 - Tropical Rainfall Measuring Mission (TRMM)

1. OUTREACH PHILOSOPHY

Since the launch of TRMM in November 1997, the education and public outreach (E/PO) program has disseminated a wide range of products (datasets, visualizations, science highlights), utilizing a variety of resources (printed media, video, DVD, world wide web, television outlets, and museums), to target a diverse audience (middle and high school, undergraduates, general public). TRMM E/PO has emphasized the following themes: 1) the spectrum of TRMM science encompasses space and time scales ranging from microscopic interactions of cloud particles that give rise to rain, to the behavior of familiar storm systems such as hurricanes, to global/interannual shifts in rainfall patterns that accompany El Nino; 2) TRMM is about much more than just measuring rainfall since it also emphasizes the connection between rain and energy in the atmosphere, rain and lightning, rain and aerosols/atmospheric pollutants, and links between ocean surface temperature and precipitation; and 3) while TRMM plays a unique science role, it also complements the larger constellation of NASA, NOAA and military Earth orbiters, acting both as a calibrator and as a provider of measurements designed to better understand Earth's complex cycling of energy and water.

2. ACHIEVEMENTS TO DATE (1997-2007)

2.1 Outreach activities

Beyond science and mission information, the TRMM website (http://trmm.gsfc.nasa.gov) is a vital tool for formal and informal public education and outreach. This cornerstone of TRMM E/PO provides an up-to-date collection of (a) formal education materials; (b) current maps of global rainfall accumulation; (c) archived visualizations of extreme rain events (such as flash floods and tropical cyclones) with accompanying descriptions; (d) links to TRMM datasets, including datasets viewable within Google Earth; and (e) a database of published TRMM research papers. The centerpiece of the web site is a feature story on the latest TRMM observations of recent significant heavy rainfall events, including tropical cyclones and flood producing storms. Readily accessible links on the TRMM website guide the user to images depicting the latest rainfall perturbations induced by El Nino and La Nina, maps showing areas of dangerous flood potential based on rain history and rain rate, graphics depicting rainfall accumulations and life-cycle changes in precipitation structure of past hurricanes (1998-2005), three-dimensional rain structure in active tropical cyclones around the world, real-time 3-hourly and 7-day accumulated rainfall, and the TRMM library of educational resources. Our global rain maps are updated every three hours and no other website provides such a comprehensive snapshot and 7-day history of rainfall at relatively high resolution (0.25 x 0.25 degree) and near-global coverage.

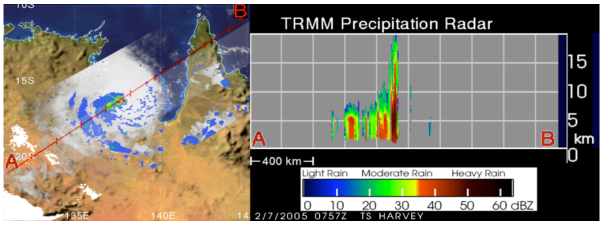

Figure 1: Analysis frame taken from 3D TRMM precipitation radar movie showing rain intensity and vertical structure in Tropical Storm Harvey. Extremely tall convective tower (20 km high) was associated with severe damage produced by the storm as it moved onshore.

We have developed a means by which visualizations of TRMM Precipitation Radar data can be more effectively utilized by the public, research, and operations communities. There is a wealth of potentially useful information on rainfall vertical structure in hurricanes, but these data have not been available in real time. Our recently developed product (Fig. 1) provides near-real-time analysis of PR data in an interactive, animated, 3D format. The visualization tool utilizes a simple interface that allows scientists, graduate and undergraduate students, and the public to better understand tropical cyclone structure over the data-sparse oceans. Oftentimes, key structural clues – such as extremely tall convective rain clouds in the eyewall (see Fig. 1) – portend sudden intensification of the storm. The product is automatically generated during each TRMM overpass of an active named cyclone anywhere in the world. The web site also contains the very recent addition of rainfall accumulation and structure plots utilizing data from the TMPA rainfall product for past hurricanes that can be used for case studies and model verification.

TRMM data is often viewable or featured on other web pages. We regularly port TRMM observations on landfalling tropical cyclones and catastrophic floods directly to NASA's Earth Observatory (EO) website (http://earthobservatory.nasa.gov). EO has greatly improved the visibility and accessibility of TRMM products as they regularly feature our visualizations and descriptions of events in both the Natural Hazards and Image of the Day sections. Web news stories and

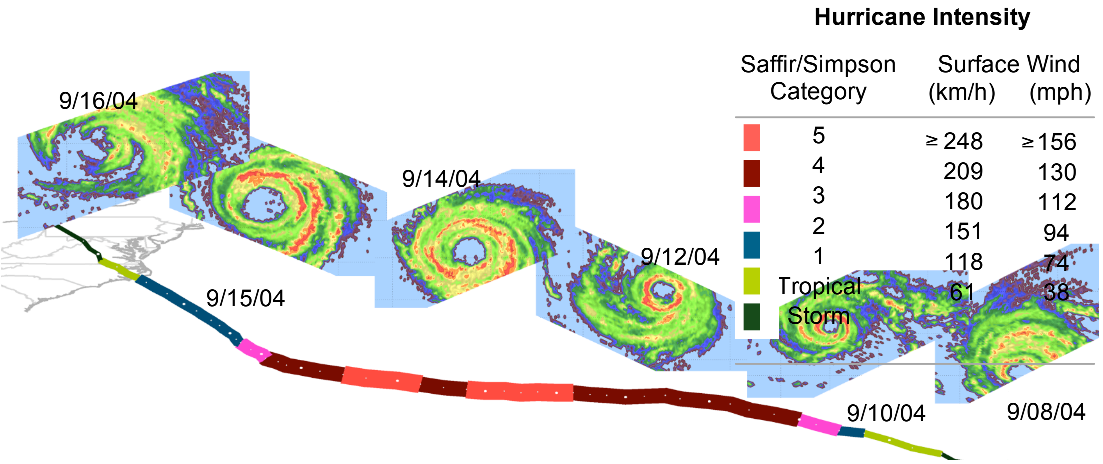

Figure 2: Mosaic of TRMM overpasses of Hurricane Isabel crossing the Atlantic.

graphic stills and animations featuring TRMM observations of hurricanes appear regularly on the NASA Hurricane Resource Page (http://www.nasa.gov/mission_pages/hurricanes/main/index.html). TRMM data are readily available for online viewing via the NASA Giovanni (GES-DISC Interactive Online Visualization and ANalysis Infrastructure) TRMM Online Visualization and Analysis System (TOVAS, http://disc2.nascom.nasa. gov/Giovanni/tovas/).

TRMM E/PO scientists have helped NASA Goddard and Headquarters Public Affairs draft more than 50 press releases since 1998. Articles highlighting TRMM science findings on urban rainfall have appeared in *Time* magazine. Articles featuring TRMM visualizations of Atlantic hurricanes appeared in the August, 2005 and August, 2006 issues of *National Geographic*. A monthly column in *Weatherwise Magazine* written by Dr. Jeff Halverson, former TRMM Outreach Scientist, frequently highlights the TRMM satellite and other NASA remote sensors such as MODIS. Chapters describing the state of science in global rainfall and tropical cyclones will appear in a mass-market Earth science book entitled “Our Changing Planet” to be published by Cambridge University Press, and will prominently feature images from TRMM (Figure 2). During the active Atlantic hurricane seasons of 2003-2005, Drs. Marshall Shepherd (past TRMM E/PO scientist) and Halverson described how TRMM was revolutionizing the way we understand hurricanes on national television. The media tour included appearances on more than 60 local television networks, CNN, Larry King, NOVA and The Discovery Science Channel. To support the appearances, several signature 3D visualizations of Hurricanes Isabel, Charley, Katrina and Rita were created by the Goddard Scientific Visualization Studio (SVS). These treatments showed millions of viewers how TRMM effectively "sees through" the clouds of hurricanes, identifying the patterns of rain (much like taking a CAT scan) and how the structure provides clues about storm intensity change. Comprehensive sets of visual treatments utilized in the 2003-2005 media campaigns can be obtained online at http://svs.gsfc.nasa.gov/ search/Instrument/TRMM.html and http://www.nasa.gov/mission_pages/hurricanes/multi-media/mm_gallery.html.

2.2 Formal and informal educational resources targeting K-16 and the general public

A series of inquiry-based formal education modules in support of TRMM and titled "Investigating the Climate System" was commissioned from the Institute for Global Environmental Strategies (IGES). These modules, which highlight Clouds, Energy, Precipitation, Weather and Winds, are separately downloadable from the TRMM website. These materials include teacher’s guides, lessons and activities with supporting animations. In addition, downloadable educational models on rainfall climate, hurricanes, lightning and the water cycle were developed in collaboration with Mrs. Leslie Bridgett, a teacher from Charles County, MD, and TRMM-based modules were developed in collaboration with Mrs. Annette de Charon at the Gulf of Maine Aquarium.

For informal public education, a 20-min video titled "Tropical Rainfall: Earth's Invisible Engine" was produced in collaboration with Jim Lynch and Associates. The video presents an overview of the TRMM mission, the types of observables collected by the satellite, and a sampling of key science findings. In 2004, the video was updated with a DVD, produced in-house. The DVD contains over an hour of narrated science stories, targeting a general audience. The goal of the DVD is to illustrate TRMM's contributions to understanding global rainfall variability, the central role of tropical rainfall in the global atmospheric water and energy cycle, and the rainfall-energy connection in powering tropical cyclones. Ten science vignettes, each 1-2 minutes in length and downloadable from the TRMM website, distill these three broad scientific themes into smaller learning topics such as the connection between global rainfall and lightning or the relationship between global cloud cover and rain intensity. These vignettes are useful enabling tools for educators and students alike.

For five years at NASA GSFC, undergraduates have had the unique experience of experiencing first-hand the complex task of maintaining satellites in orbit, including TRMM, under a grant sponsored by the Space Operations Institute of Capitol College. The students learn how to perform routine TRMM orbit-maintaining operations in the NASA GSFC control center and work side-by-side with professional controllers. They load memory, download data recorders and perform trending and analysis calculations. In addition to becoming certified in satellite operations, Capitol College attempts to place the students into control-related careers in the satellite missions support industry.

TRMM E/PO scientists have lectured to groups of Earth science teachers at Goddard workshops, have engaged students in science distance learning utilizing the video classroom, and have presented TRMM science highlights to numerous universities. TRMM visualizations have been featured in presentations at the Science Museum of Minnesota under the direction of Dr. Alan Nelson. A unique animation of Earth data, called Earth Today, is on exhibit at the National Air and Space Museum. The animation, narrated by James Earl Jones, is continuously updated with the most current rainfall data provided by TRMM and other sensors. Earth Today provides a powerful means of engaging the public in the current state of the planet and shows the important connection between rainfall and other geophysical datasets.

3) TRMM E/PO PLAN FOR 2007-2009

3.1 Outreach

The TRMM E/PO group at NASA Goddard will continue its mission of broadly disseminating TRMM highlights and scientific findings using the spectrum of tools identified above (i.e. media campaigns, popular magazines, DVD, websites, museums, invited lectures and talks). An essential component will be maintaining student involvement in the Capitol College satellite missions support program. However, there are several thematic changes to E/PO which will be required to transition TRMM E/PO into the Global Precipitation Measurement (GPM) mission era. GPM is the follow-on for TRMM, consisting of a constellation of satellites, targeted for launch in 2013. GPM will expand precipitation measurement out of the tropics and subtropics into high latitudes and will provide additional information on the microphysical properties of precipitation. The mandate of E/PO will be to become less mission-centric, and concentrate instead on the global-scale measurement and science of precipitation from space, including frozen forms of precipitation such as ice and snow. Our existing focus of TRMM in the tropics and subtropics will be meshed with extratropical precipitation processes such as fronts and migrating storms in the jetstream. These processes impact a great number of people across North America, Europe, and Asia every day throughout the year, as opposed to the occasional tropical cyclone in the fall season or an active El Nino year. A step in this more globally integrated direction is already in place in the form of the TRMM-based Multi-Satellite Precipitation Analysis which features prominently on our web site. In addition, ongoing and parallel efforts to quantify longer-term global rainfall variability, such as the Global Precipitation Climatology Project (GPCP), will be blended under the umbrella of a more precipitation-centric outreach effort.

Secondly, our E/PO efforts are engaged in identifying more effective ways at conveying the concept that rainfall, while an important geophysical entity in its own right, cannot be treated in isolation from the larger Earth water cycle and Earth systems. In the GPM-era, more emphasis will be placed on the societal impacts of rainfall such as devastating floods, the impact of rainfall on soil moisture, agriculture, the health of ecosystems, and freshwater management. Our education and outreach efforts should reflect this shift in paradigm – how can we identify ways in which precipitation science better serves society? By adopting a more holistic or Earth Systems framework, we will combine TRMM/GPM datasets and visuals with remote sensors that graphically portray the aftermath and consequences of heavy rain input into watersheds. In addition, we are exploring ways of partnering with joint NASA-NOAA-USGS efforts to better identify regions that are prone to deadly landslides, such as the Caribbean and Central America. An important component of TRMM/GPM outreach will be to illustrate and identify regions where torrential rainfall coincides with landslide vulnerability. Space-based monitoring and web-based dissemination of this information can serve as a powerful educational tool to warn of susceptibility.

3.2 Formal and informal education

Activities directed toward formal and informal education are being addressed in a proposal to NASA ROSES, led by John Leck of Goddard's Education office in collaboration with four Goddard members of the Precipitation Measurement Mission science team. The proposed activity includes the development of lessons for middle school students on the science content of the PMM science team members' projects. Two middle school teachers will be hired for one month each to work with the scientists to develop lessons that align with National Science Education Standards and incorporate visualizations created by the GSFC Public Affairs Office/Scientific Visualization Studio. Data tools such as the NASA Earth Observations (NEO) and the Image Composite Editor (ICE) tool will be utilized as well. NEO utilizes a web-based platform that easily integrates user-defined data into ICE as well as GIS tools such as WorldWind© and Google Earth©. The initial focus for the lessons will be on the NASA Explorer Schools (NES) in the GSFC region. The schools in this program are chosen based upon their being a part of underserved communities (see http://explorerschools.nasa.gov/portal/site/nes/). Improvements in the lessons will be made based upon evaluation by the NES. The lessons would eventually be shared with schools around the country through the Aerospace Education Services Program (AESP). In addition to the NES, with the assistance of the Tribal Colleges Office at GSFC, all lessons will be made available to Native American schools through the American Indian Higher Education website (http://www.aihec.org). The lessons developed by this proposal will also be used to create educator packets for Science On a Sphere (SOS), including lessons for students to complete before and after viewing SOS.

The primary target audience for informal education activities will be museums and science centers, as well as the science attentive public. Working with the PMM scientists, the Scientific Visualization Studio will create visualizations, animations, and graphics that highlight or explain the scientific findings of the PMM science team members. Presentations will be developed for use on multiple platforms and data will be formatted for use in tools such as NEO and ICE and for presentation media such as SOS, Magic Planet® (http://www.globalimagination.com/), and ViewSpace. Presentation materials will be archived on the NASA web portal for use by museums, science centers, classrooms, and others interested in precipitation science. Finally, a "Precipitation Watch" web page will be designed to keep information on NASA's role in understanding precipitation and climate change on a useful and easy-to-use web site. The format for the web page would be modeled after the "Ozone Watch" website (http://ozonewatch.gsfc.nasa.gov) and would contain links for education, multimedia, meteorology, and precipitation facts.

Evaluations of these efforts will be based upon feedback from educators, museums, and science centers. The AESP will gather data from teachers on the usefulness and effectiveness of lessons. Data can also be collected on students' pretest and posttest results. Museums and science centers will be surveyed each year to determine if their needs are being met.