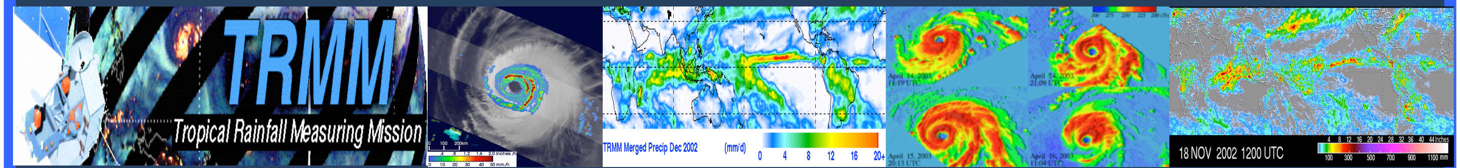
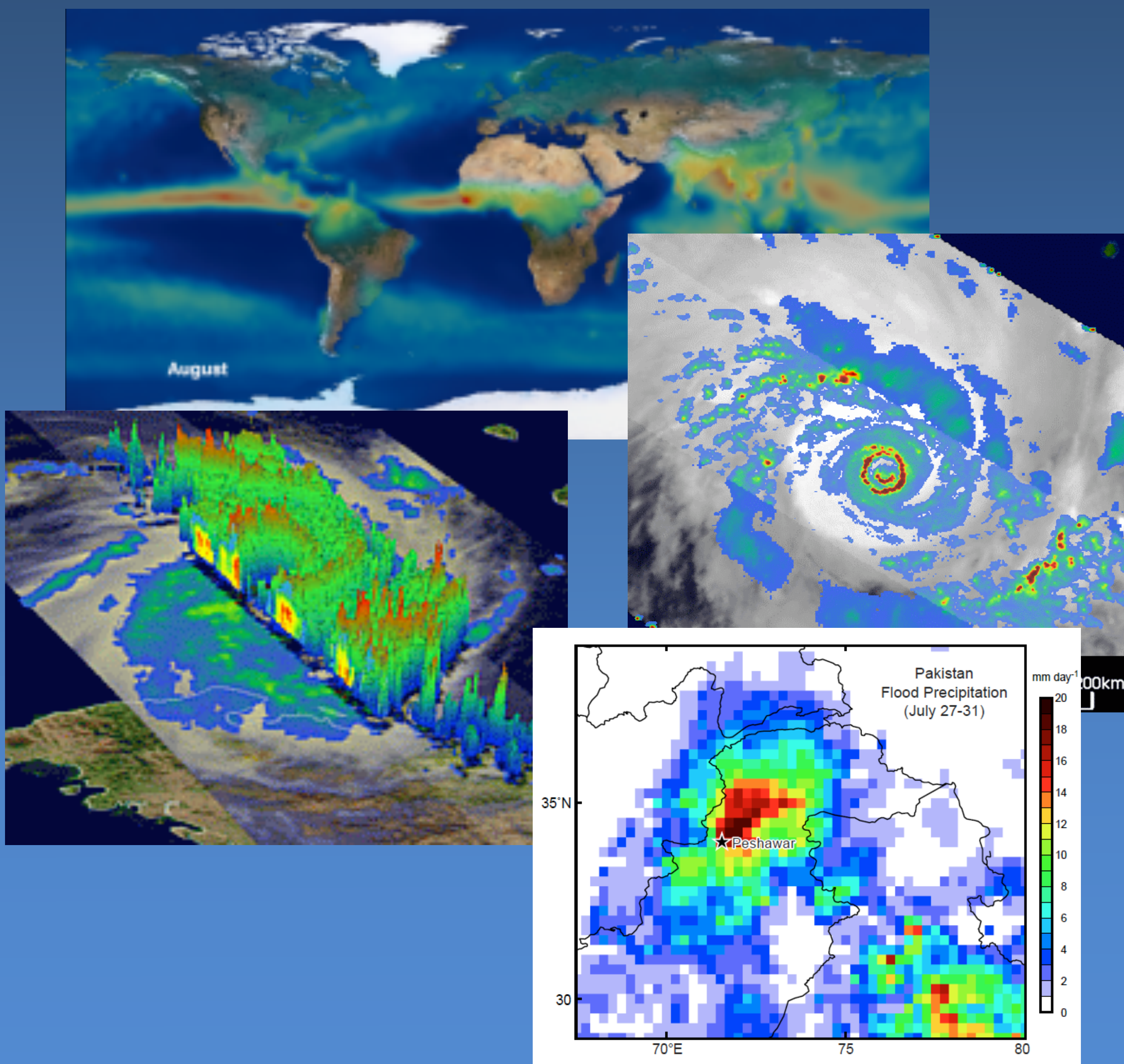


Tropical Rainfall Measuring Mission

Senior Review Proposal

2011



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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 2006 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 fulfillment of national operational objectives through use of TRMM data, primarily in the monitoring of tropical cyclones**, in hydrological applications and in assimilation of precipitation information into forecast models.

Extension of TRMM will result in: 1) an improved climatology of precipitation characteristics, especially extremes; 2) diagnosis and testing of inter-decadal and trend-related processes in the water cycle; 3) assessment of the impact of humans on rainfall characteristics and processes; 4) robust determination of convective system, tropical cyclone, and lightning characteristics; 5) advances in hydrological applications over land (basin-scale assessments, water management); 6) improved modeling of the global water/energy cycles for weather/climate predictions; and 7) 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 potentially maintain science operations until 2014 or later. TRMM flight operations and data processing costs have been significantly reduced for the extension period. TRMM data processing has shifted 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 extension will continue production of validation products that continue to contribute toward algorithm validation and improvement. **A multi-year extension of TRMM has a very high payoff for science and applications, but at a low additional cost to NASA.** In 2003, TRMM was merged with the GPM mission under the umbrella of the Precipitation Measurement Missions program, with the TRMM Senior Review budget being responsible for both TRMM and GPM activities. TRMM will be able to accomplish its goals within the guideline budget. GPM-related activities are increasing as launch approaches in 2013, with emphasis on development of precipitation algorithms designed for the GPM instrument suite and for mid-latitude precipitation. While the GPM goals can be achieved within the current guideline budget, cuts to TRMM/GPM would impact GPM algorithm development and validation.

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1. TRMM MISSION BACKGROUND

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 2011. 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 2013 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 Earth Observing System (EOS)-funded instrument, has complemented the rain sensors, 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. Detailed information on the TRMM instruments is given in Section 2.1.2.

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 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 package instruments (PR, TMI, VIRS) and the LIS have

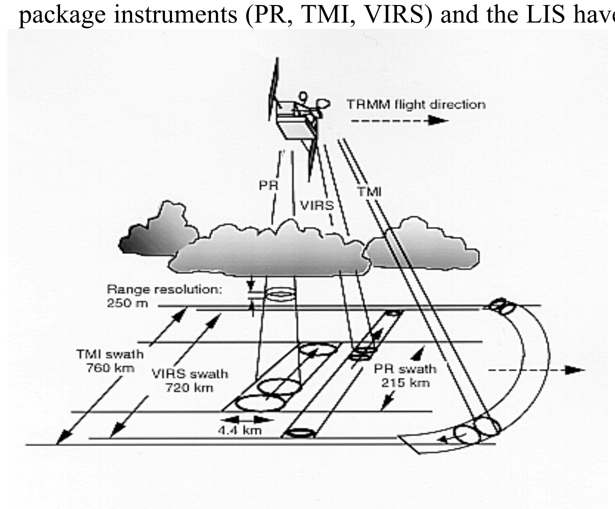

Fig. 1. Schematic of TRMM satellite and scanning geometries of three rain package instruments.

Table 1. TRMM Sensor Summary – Rain package

	Microwave Radiometer (TMI)	Radar (PR)	Visible and Infrared Radiometer (VIRS)
Frequencies	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
Resolution	11 km X 8 km field of view at 37 GHz	5-km footprint and 250-m vertical resolution	2.5-km resolution
Scanning	Conically scanning (53^0 inc.)	Cross-track scanning	Cross-track scanning
Swath Width	880-km swath	250-km swath	830-km swath

functioned nearly perfectly for over eleven years, the only exception being a two-week period in June 2009 in which the PR experienced a temporary component failure (see section 3.1.3).

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 (~ 9.5 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 combination of active-passive 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.

2. TRMM SCIENCE

2.1 TRMM Project Science

TRMM was the first NASA Earth Science mission focused on the measurement of precipitation. Its success is a key motivation for the more advanced GPM mission to be launched in 2013. Project scientists for both missions are located at Goddard. In 2003, because of their mutual focus on precipitation and shared needs for project office support, algorithm development, and ground validation assets, both missions were merged under the umbrella of the Precipitation Measurement Missions (PMM) Program. TRMM and GPM science, including research using TRMM data, algorithm related science, and research using TRMM ground validation (GV) operational data sets, has since been funded via ROSES PMM funding. The TRMM non-ROSES Data/Analysis (DA) budget has supported the project office (e.g., grant and meetings support, E/PO); algorithm implementation, testing, and maintenance; GV site support and generation of routine operational GV products; and, until recently, TRMM data processing.

This section describes the mission operations, instruments, data processing, and ground validation program. A description of the status of mission operations, the spacecraft, and the instruments can be found in the Technical section of this proposal (section 3). Section 2.2 presents the scientific accomplishments in TRMM-related science, with emphasis on the past two years. Section 2.3 describes the science objectives that may be achieved with an extended TRMM mission. Section 2.4 provides the statement of work.

2.1.1 Mission operations

TRMM spacecraft flight operations activities are managed by the Earth Science Mission Operations (ESMO) Project at Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. The Flight Operations team is responsible for flight planning, monitoring the health and safety of the spacecraft, coordinating science 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 all 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 requests 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 an overflow mode that will cause no new data to be recorded.

The TRMM Operations Control Center (OCC) located at GSFC is presently operating in a lights-out mode of operations and is staffed fifteen hours per day, on weekdays (15x5), 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 10:00 PM to 7:00 AM, Monday through Friday, 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 Command and Data Handling (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 on-board spacecraft capabilities and the SN/White Sands Ground Terminal (WSGT) support reliability. The success of the automation is reflected in the high data-capture rate of instrument data during calendar years 2009 and 2010. The overall data-capture rate for the TRMM mission was 99.93% and for all the operational instruments was as follows:

Data Recovery		
Instrument	**2009**	**2010**
PR	94.75	99.56
VIRS	99.93	99.88
TMI	99.88	99.97
LIS[1]	99.59	99.87

The LIS is technically an EOS instrument flying on TRMM. Marshall (MSFC) is the responsible facility for the LIS.

2.1.2 Description of the TRMM instruments

<u>*Precipitation Radar (PR).*</u> *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 ±17º (250-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.

<u>*TRMM Microwave Imager (TMI).*</u>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.

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 NOAA series of spacecraft. The major differences between the two systems are the 2.5-km nadir IFOV for VIRS in contrast to 1.1 km for the AVHRR and the fact that the VIRS has an on-board solar diffuser for post launch calibration of the two reflected solar bands.

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 4 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).

2.1.3 TRMM precipitation data processing

The TRMM Science Data and Information System (TSDIS) was retired as the data processing system for TRMM in June 2008. Given budget cuts received virtually every year since 2005, it was no longer possible to maintain the software and the hardware for the system. In June 2008, an early version of the Precipitation Processing System (PPS), being designed for the GPM mission, was implemented to assume TRMM data processing. FY09 was the last year that any funds were directly allocated for TRMM data processing operations. Effective June 2008, TSDIS software was no longer maintained. Effective April 2009, the TSDIS data product toolkit was replaced by the PPS toolkit. While this toolkit was substantially untested in production and required major code changes for the algorithm developers, the change was necessary so that programmers were not required to maintain the TSDIS toolkit and all toolkit activity could be subsumed under PPS support to GPM.

PPS is producing all the PR, TMI, VIRS, combined instrument and multi-satellite standard products. There has been little or no perceivable degradation in instrument performance since launch. The PPS produces up to 12 GB/day of initial science data from the satellite. PPS 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 (instrument counts reversible to L0). PPS 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 distribution to the general public and for user support for this group. PPS also has responsibility for reprocessing of TRMM data in the next year using the Version 7 algorithms. The reprocessing requirement is to provide an additional 2X (24 GB additional) satellite data reprocessing. Changes for V7 reprocessing are currently being implemented by the algorithm developers and PPS. Operational testing for V7 algorithm code is under way and is expected to be completed by May 1, 2011.

PPS also 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). Indeed, an upgraded version of the TMPA was put into operation in February 2009. In addition to the standard products provided to the wider community via an online archive, PPS 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. The last hardware upgrade to support TRMM processing was undertaken in 2008.

At the request of some PMM science team members, PPS produces 0.25 by 0.25 deg gridded text products. These products are available online from the PPS TRMM server. In addition, a TIFF/world file version of the TMPA real-time and production products were made available to GIS data users. The latter was done as a prototype for the delivery of precipitation data in GIS compatible formats during GPM.

The continuation of the TRMM basic mission means the continued production of 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 mid 2011. This level of data production is provided as in-kind support as part of the PPS budget.

2.1.4 LIS data processing

The LIS data processing chain includes ongoing monitoring of LIS instrument health, instrument command requests from MSFC to the GSFC Flight Operations Team (FOT), transference of raw level 0 LIS data from the GSFC TRMM Missions Operations Center (MOC) to the LIS Science Computing Facility (SCF), and further processing of level 0 data at the SCF for product generation, quality control, archival and distribution.

The processing of level 0 LIS data at the SCF is conducted at the National Space Science and Technology Center (NSSTC) in Huntsville, AL. It includes the routine generation of high level LIS products (e.g., flash locations, flash optical properties, and various lightning climatology products). It also includes the maintenance of the LIS processing algorithms and code responsible for generating these high-level products. Note that the high level product orbit files are quality controlled, archived and distributed. The Global Hydrology Resource Center (GHRC) manages the archival/distribution services for LIS data with support it receives from the LIS budget. The GHRC, also located at the NSSTC, is a NASA EOS DAAC supporting the hydrological cycle. LIS data access is available from the following website http://lightning.nsstc.nasa.gov/data/index, which indicates: *"Data can be ordered free of charge from the GHRC through HyDRO, the GHRC's online data ordering system, or by contacting the GHRC User Services Office."* The HyDRO website is http://ghrc.nsstc.nasa.gov/hydro/.

As part of the archival and distribution services, user community feedback is routinely gathered that allows the LIS team to refine and evaluate existing products and to introduce new products of specific relevance and importance. These activities motivate the science tasks described in the LIS statement of work (section 2.4.2). Moreover, because the LIS observational time-series now extends beyond 13 years, it has attained significant statistical information content that allows for the creation of several more useful products for the science user community. Recent examples include the creation of a higher spatial resolution lightning climatology (to 0.25^{o} latitude/longitude bins), the creation of cell-scale databases which combine lightning and other TRMM products (e.g., reflectivity volumes, brightness temperatures, hydrometeor contents etc.) on convective scales, and the creation of VHF-optical lightning proxies for use in testing and improving GOES-R Geostationary Lightning Mapper algorithms.

2.1.5 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, rain gauge and disdrometer 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). There is also a significant effort being supported at NASA Wallops Flight Facility (WFF) to provide high quality, long-term measurements of rain rates (via a network of rain gauges collocated with National Weather Service gauges), as well as drop size distributions (DSD) using a variety of instruments, including impact-type Joss Waldvogel, laser-optical Parsivel, as well as two-dimensional video disdrometers. DSD measurements are also being collected at Melbourne and Kwajalein using Joss-Waldvogel disdrometers. 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 carefully quality control ground radar data sets and estimate 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. 2008). 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.

The TRMM GV program has made significant accomplishments over the last several years. A methodology to monitor and correct radar reflectivity calibration using ground clutter area reflectivity distributions, referred to as the Relative Calibration Adjustment (RCA) methodology (Silberstein et al. 2008), is now fully operational and has provided near-real-time feedback to Kwajalein radar staff of any possible issues with the Kwajalein radar. This RCA has the ability to detect and correct past changes in radar calibration (±0.5 dB) and antenna elevation pointing errors (±0.1°), but is also prescient in detecting impending failures of the radar system. Application of the RCA to correct the historical data record for Kwajalein has salvaged a vital and irreplaceable climate precipitation record (12+ years) at this key oceanic GV site. Through the use of dual-polarimetric (DP) data from the Kwajalein radar (KPOL), an algorithm has been adapted to determine absolute reflectivity calibration by a self-consistency approach thereby verifying the RCA methodology. In addition, an automated QC algorithm based on DP observations has been adapted for the Kwajalein site. The DP-based QC application is statistically robust, and significantly reduces labor-intensive processes needed when utilizing non-DP radars (Marks et al. 2011).

The Tropical Rainfall Measuring Mission (TRMM) GV program was originally aimed toward a statistical approach to precipitation retrieval validation; however, the current paradigm for both TRMM and future missions, such as the Global Precipitation Measurement (GPM) program, will also employ physically based approaches to validate satellite observables and parameterizations. A key goal of this physically based approach is to characterize the raindrop size distribution (DSD) of precipitation, as well as the microphysical structure of the precipitating system: e.g. the vertical distribution of liquid, mixed-phase, and solid hydrometeors. With the recent advent and deployment of DP radars, it is now possible to provide estimates of the key raindrop size distribution parameters (median/mass weight particle diameters and concentrations), at least within the rain (liquid) layers. Additionally, use of polarimetric variables, such as differential reflectivity (Z_{DR}) and specific differential phase (K_{DP}) can be used to provide improved rain estimates, characterize the horizontal and vertical distribution of the various hydrometeor types, and characterize the height and depth of the mixed layer. From a physical validation perspective, the combination of DSD parameter retrievals and hydrometeor classification facilitated by DP radars provides an important means to cross-validate microphysical parameterizations in GPM Dual-frequency Precipitation Radar (DPR) and GPM Microwave Imager (GMI) retrieval algorithms (Chandrasekar et al. 2008). Analysis of KPOL data have shown that the quality of its DP parameters are comparable to established research radars, and are well suited for implementation of QC, rain rate estimation, and hydrometeor classification algorithms (Marks et al. 2011).

GV products are used extensively by many groups for validation research and published in peer-reviewed journals (Fisher and Wolff 2011; Liao and Meneghini 2009; Huffman et al. 2007; Marks et al. 2009, 2011; Munchak and Kummerow 2011; Schwaller and Morris 2011; Tokay and Bashor 2010; Tokay et al. 2010; Wang et al. 2008; Wang and Wolff 2009, 2010; Wolff and Fisher 2008, 2009). Munchak and Kummerow (2011) used KPOL-derived DSD parameters to develop a framework based upon optimal estimation theory, wherein three parameters describing the raindrop size distribution, ice particle size distribution, and cloud water path are retrieved for each radar profile to provide improved rain rate retrievals for the TMI and future GMI. Liao and Meneghini (2009) used a decade long record (1998-2007) of GV radar data from Melbourne, FL, radar to assess the robustness of the TRMM PR attenuation correction. Schwaller and Morris (2011) used TRMM GV data and QC algorithms to develop a prototype validation network over the southeast United States to support TRMM GV efforts, GPM pre-launch algorithm development, and eventually validation of GPM space-based rain rate retrievals.

TRMM GV members continue to work closely with satellite product algorithm developers to help validate and tune products, and also provide important input to the land-algorithm working group for GPROF. TRMM GV data is being used to provide validation for several global precipitation products, such as TRMM 3B42 (Huffman et al. 2007), the Climate Data Centers' Morphing product (CMORPH, Joyce et al. 2004) and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), developed by Hsu et al. (1997).

Because of the highly variable nature of precipitation, it is important to have high quality validation data from a diverse variety of cases and climate regimes over extended time periods. Therefore, it is imperative for these products to cover many seasons and inter-annual variations in order to effectively sample the natural variability of precipitation and other characteristics with which to validate satellite estimates. Further, long-term observations are necessary to provide robust validation of satellite estimates, given the rarity of significant precipitation events at a given site. Sub-setting and validating the data over land, coast and oceanic areas is needed for algorithm developers to tune their estimates over varying land surfaces. Continuous validation is also important for monitoring the health of the various satellite instruments, which might decay over the lifetime of the platform. For these reasons, the TRMM GV program has continued to collect and process data and should continue to do so in the future in synergy with the broader validation program of GPM.

2.2 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 now at 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 products are used extensively by the

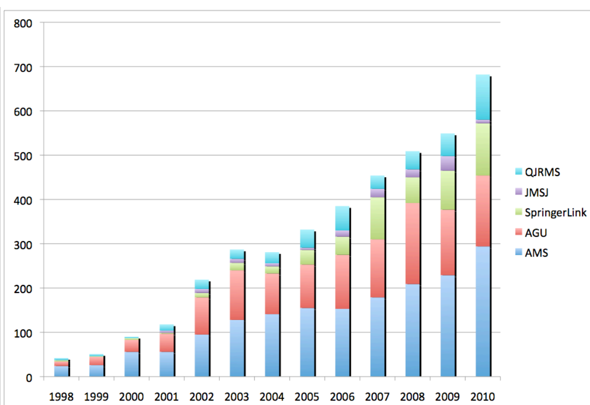

Fig. 2. Publication data show yearly totals broken down by journal publisher. Totals are obtained by searching publisher web sites for papers that mention TRMM within the article text. Colors are as follows: light blue, AMS; red, AGU, green, Springer-Link (e.g., Meteorology and Atmospheric Physics); purple, J. of the Met. Society of Japan; cyan, Quarterly Journal of the Royal Met. Society.

research (sections 2.2.1 through 2.2.3) and applications communities (sections 2.2.4 and 2.2.5). 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 over 2000.* A partial listing can be found at http://trmm.gsfc.nasa.gov.

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. TRMM's original science goals have been met and many additional contributions have been made, beyond what was originally expected.

2.2.1 Climate-related research

Rainfall climatology. TRMM's new knowledge on rain distribution across the tropics has led to **a benchmark 13-year TRMM rainfall climatology (Adler et al. 2009), narrowing considerably the range of uncertainty in previous space-based rainfall estimates**. It provides unique monitoring of rainfall variations related to the stationary interannual ENSO pattern (L'Ecuyer et al 2006; Arndt et al 2010) and the moving intraseasonal Madden–Julian oscillation (MJO) pattern (Lau and Wu 2010, Waliser et al. 2009). Having examined global and regional interannual variations of rainfall characteristics over the tropics, Nakazawa and Rajendran (2009) showed that TRMM datasets detect the interannual variation of rainfall in concert with OLR and SST changes, which are closely tied to ENSO. Using rainfall estimates from PR, Liu and Zipser (2009) found that warm rain (cloud-top temperatures >0°C) contributes 20% to total rainfall over tropical oceans and 7.5% over tropical land. While categorizing tropical convection into shallow, midlevel, and deep clusters, Elsaesser et al. (2010) noted that each contributes roughly 20%–40% in terms of total tropical rainfall, but with mid-level clusters especially enhanced in the Indian and Atlantic sectors, shallow clusters relatively enhanced in the central and eastern Pacific, and deep convection most prominent in the western Pacific.

Diurnal cycle. TRMM has allowed the **heretofore-impossible quantification of the diurnal cycle of precipitation and convective intensity over land and ocean tropics-wide on fine scales (0.25°)** (e.g., Nesbitt and Zipser 2003; Bowman et al. 2005; Hirose et al. 2008). In addition to studies characterizing the diurnal cycle on global scales, the continued accumulation of data has allowed for more studies of the diurnal cycle at

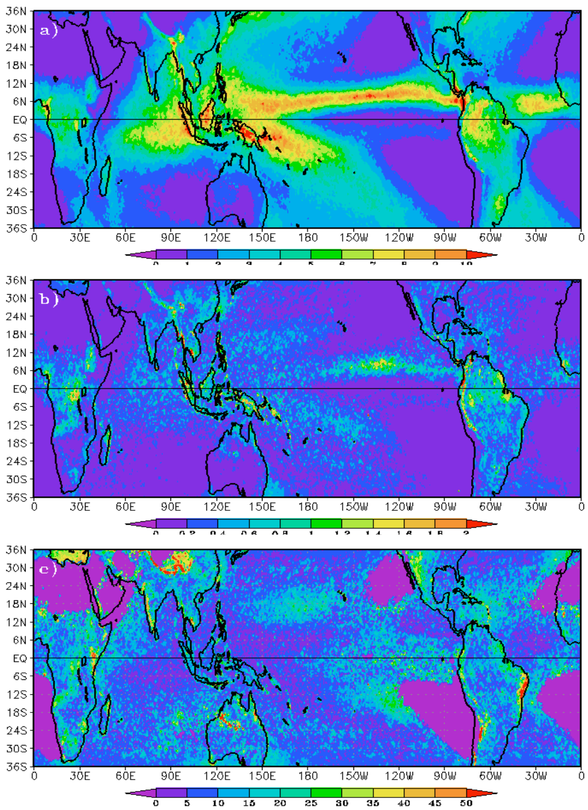

Fig. 3. a) Climatology (mm/day), b) standard deviation among the TRMM climatology inputs, and c) standard deviation/mean (%) for 10-year TRMM composite rainfall during 1998-2007. The standard deviation and standard deviation/mean are used as a measure of error or measure of confidence in the climatology. [Adler et al. (2009)]

regional scales including southeastern China (Chen et al. 2009), Indochina peninsula (Takahashi et al. 2010), India (Sahany et al. 2010) and western equatorial Africa (Jackson et al. 2009). Studies have also focused on local scales in central India, the southern Himalayan foothills, and the central Tibetan Plateau during summer monsoon periods (Singh and Nakamura 2009, 2010), and east of the eastern Tibetan Plateau during the Mei-Yu season (Xu and Zipser 2011), where the interaction of large-scale circulation and local topography plays a key role.

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,** 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, 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, 2010) for analysis and comparison with global models. Recently, with the help of extended PR convective/stratiform rainfall data, improved Convective–Stratiform Heating (CSH) algorithm-derived heating profiles were developed for the global tropics (Tao et al. 2010). In addition, the analysis of 13 years of TRMM data provides a baseline climatology of the vertical structure of atmospheric radiative heating in today's climate and an estimate of the magnitude of its response to environmental forcings on weekly to interannual time scales (L'Ecuyer and McGarragh 2010). Schumacher et al. (2008), Kodama et al. (2009), and Takayabu et al. (2010) have conducted studies of latent heating using the TRMM products.

Tropical dynamics. TRMM data has yielded new insights into **the dynamics of the tropical waves and oscillation and hypotheses on the dynamics of convective-climate feedbacks** (Masunaga et al. 2006). Using TRMM rainfall data, Lau and Wu (2010) investigated the evolution of cloud and rainfall structures associated with different phases of the MJO. They note that the structural changes in rain and clouds (Fig. 4) are consistent with corresponding changes in derived latent heating profiles, suggesting the importance of a diverse mix of warm, mixed-phase, and ice-phase precipitation associated with low-level, congestus, and deep clouds. Combining the information from TRMM latent heating profiles and rainfall rates, Zhang et al. (2010) argued that, contrary to general perceptions, radiative heating is more important than latent heating in accounting for vertically propagating tides that impose longitudinal variability on mesosphere-lower thermosphere winds, temperatures, and densities. The long record of high-resolution SST data from TMI allows **investigations of tropical waves and oscillations on different time scales.** Zhang and Busalacchi (2009) developed an empirical model for surface wind stress response to SST forcing induced by tropical instability waves in the eastern equatorial Pacific. Their model has applications for uncoupled ocean and coupled mesoscale and large-scale air–sea modeling studies.

Impact of humans on rainfall. TRMM PR data have been used to **identify rainfall anomalies possibly associated with human impacts on the environment (Lin et al. 2006).** 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. L'Ecuyer et al. (2009) revealed that polluted clouds are more vertically developed than those in pristine environments, and at the same time act to suppress the formation of precipitation, evidenced by a trend toward higher liquid water path prior to the onset of light rainfall. Hand and

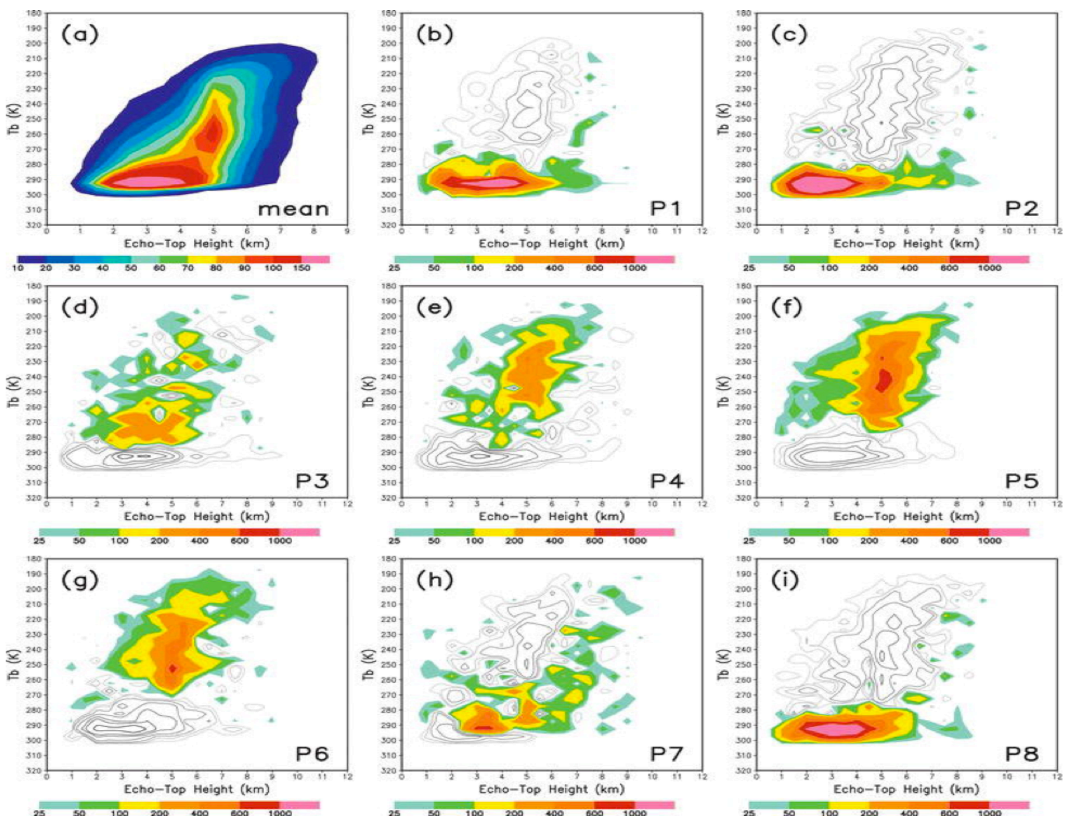

Fig. 4. Joint PDF of Tb and echo-top height over the equatorial western Pacific: (a) mean state of the eight MJO phases and (b)–(i) the difference between the Joint PDF of each of the phases 1–8 (P1–P8) and the mean state. Positive values are color shaded and negative values are in contours. The unit for the mean state is in 0.01% of the total occurrence counts. For P1–P8, the unit is number of counts. (From Lau and Wu 2010)

Shepherd (2009) suggested that the TRMM rainfall estimates may be used to examine rainfall modification by urbanization on global scales and in parts of the world not well instrumented with rain gauge or radar networks. Changes in rainfall and lightning resulting from human activities are also studied for many climatologically important regions as well as urban environments. Over the southeastern U.S. and nearby Atlantic waters, summertime rainfall was found to be significantly higher during the middle of the work week than on weekends (Bell et al. 2008), which was related to the regional climate-scale impact of aerosols from anthropogenic air pollution. An improved storm height analysis indicates that the probability of deeper storms (7–15 km) are increased during the afternoon and evening hours of midweek (Bell et al. 2009).

2.2.2 Convective systems and tropical cyclones

<u>Convective systems characteristics.</u>

TRMM PR, TMI, VIRS, and LIS supply information for a Cloud and Precipitation Feature (CPF) database, created by the University of Utah, that **provides a definitive climatology of the distribution of convective system characteristics (e.g., horizontal size, depth, and intensity) which is very useful for searching and sorting historical rainfall events (Liu and Zipser 2005).** The CPF database has been used to document the global distribution of tropical deep convection (Liu et al. 2007), and to examine regional, seasonal and diurnal variations of the rainfall contributions from various precipitation features (Liu 2011). Seasonal variations of sizes and intensities of precipitation systems are found over the northeastern Pacific, Northern South Pacific Convergence Zone (SPCZ), and some land areas in addition to the well-known monsoon regions. A significant advantage of PR data from other satellite-based rainfall measurements is that it provides not only spatial information on rainfall, but also vertical profiles of precipitation. Therefore, it is frequently used to **characterize the vertical structure of convective system in many climatologically important regions** such as South America (Romatschke and Houze 2010), western equatorial Africa and the adjacent Atlantic (Jackson et al. 2009), and the south Asia monsoon region (Romatschke and Houze 2011a, 2011b). Houze et al. (2011) used TRMM data in an analysis of the

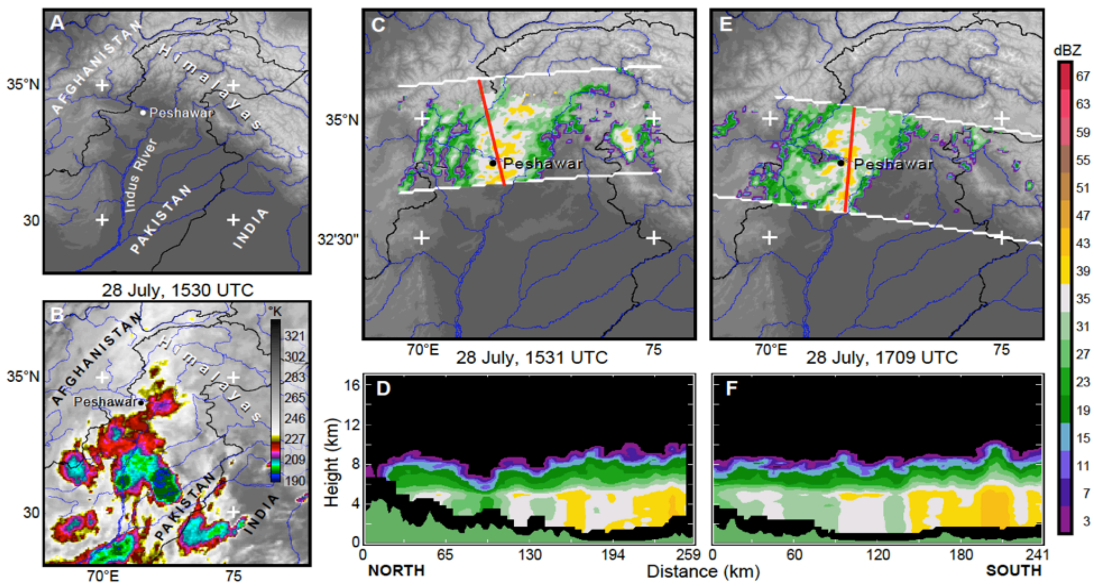

Fig. 5. (a) Topography and (b)-(f) satellite data for the 28 July 2010 Pakistan rainstorms. (b) Infrared satellite image (K) from METEOSAT 7 for 1530 UTC 28 July. (c)-(f) Reflectivity from the TRMM satellite radar in dBZ. (c)-(d) TRMM radar overpass at 15:31 UTC 28 July. (e)-(f) TRMM radar overpass at 1709 UTC 28 July. Horizontal cross-sections are at 5 km altitude. Red lines in (c) and (e) indicate the locations of the vertical cross-sections in (d) and (f), respectively.

devastating floods in Pakistan in 2010 (Fig. 5). Using multiple years of TRMM data, convection has been characterized in regions where topography plays a critical role in the spatial and temporal distribution of precipitation, including the central Andes (Giovannettone and Barros 2009), central and southern Mexico (Gebremichael et al. 2007), and the Tibetan Plateau (Li et al. 2008). Moreover, a daily soil analysis (Gao et al. 2006) from TRMM provides an opportunity to study the relations between convective initiation and soil moisture and its gradient (Frye and Mote 2010).

Tropical cyclones. Over the past decade, **TRMM TMI and PR data have been heavily used by the National Hurricane Center (NHC) (Rappaport et al. 2009), and have played an important role in the monitoring and analysis of tropical cyclones (e.g., Blake and Pasch 2010; Kimberlain and Brennan 2011).** The data have helped establish key characteristics of the distribution and variation of rainfall in tropical cyclones as a function of intensity, stage of development, and environmental conditions (Lonfat et al. 2004, Chen et al. 2006). The ability of TRMM to see within cloud systems enables it to **detect the clouds within the inner regions of topical cyclones**. It aids the analysis of clouds and precipitation associated with the different parts of tropical cyclones including the eyewall and the rainbands beyond the eyewall region (Houze 2010). Jiang and Zipser (2010) estimated that the contribution of tropical cyclones to the total rainfall over six oceanic basins during tropical cyclone season range from 3-11%, with the maximum percentages in the eastern Pacific near the Baja California coast, in the southern Indian Ocean close to the Australian coast, and in the northwestern Pacific near Taiwan. Combining the TRMM multi-satellite precipitation product with MODIS and AIRS data and with NCEP global analyses, Braun (2010a) argued that the Saharan air layer, thought to be a positive factor to hurricane development by some people but a negative factor by others, is not a determinant of whether a tropical cyclone will intensify or weaken in the days after formation. Both SST and rainfall data from TRMM are also often utilized to investigate the mechanisms responsible for the genesis of some extreme storms, e.g., hurricane Catarina, the first hurricane ever recorded in the Southern Atlantic Ocean (Vianna et al. 2010).

Lightning climatology. The use of the lightning sensor, LIS, in conjunction with rain information has led to a **detailed global mapping of lightning distribution, quantifying the lightning/convection relation for land and ocean** (Petersen et al. 2005, 2006; Takayabu 2006). Yoshida et al. (2009) suggested that the number of lightning flashes per second per convective cloud is related to cold-cloud depth (the height above the 0º C level) and that this relationship has little regional dependency. At regional scales, seasonal variations of lightning activity in precipitation systems over south China exhibited higher probabilities of lightning and higher flash rates before the onset than during the mature phase of the Mei-Yu season (Xu et al. 2010). Ten years of LIS data were used to generate higher resolution lightning climatology maps (Albrecht et al. 2009), identifying more localized features of lightning activity. Post-TRMM-boost data have been used to explore the relationship between tropical cyclogenesis and global easterly wave phenomena (Leppert and Petersen, 2010, 2011). In addition, extensive aircraft measurements of lightning and thundercloud currents can now be combined with LIS (and Optical Transient Detector, OTD) data to make modern estimates of the so called *Carnegie Curve* that characterizes the global electric circuit based on the LIS climatology and an existing fixed database of aircraft electrical measurements (Mach et al. 2009; Mach et al. 2010; Mach et al. 2011).

Lightning and chemistry. Knowledge of flash energy and flash type (ground flash or cloud flash) is crucial for better determining lightning nitrogen oxides (NOx) emissions. Through ground validation, radiative transfer modeling, and regional air quality model implementation studies, progress has been made in better understanding the value of LIS data for estimating lightning flash energy and for discriminating lightning flash type (Solakiewicz and Koshak 2008a,b; Koshak et al. 2009; Koshak 2010; Koshak 2011; Koshak and Solakiewicz 2011). In particular, the study by Koshak (2011) introduces a mixed exponential distribution model that can be used to retrieve the *ground flash fraction* in a set LIS-observed flashes; this represents the first attempt to divide the total lightning distribution into two distributions: one for the ground flashes and one for the cloud flashes. LIS data are also useful for identifying lightning generated NOx and investigating rain-induced soil NOx emission (Bucsela et al. 2010; Ghude et al. 2010).

2.2.3 Measurement advances

Improvement of algorithms. Comparison of TMI and PR rain rates has led to **increased understanding of differences between, and therefore improvements to, these retrievals and those for all passive microwave sensors** (Berg et al. 2006; Masunaga and Kummerow 2005, Shige et al. 2008). In preparation for a new version of TRMM products, i.e., version 7 of the TRMM algorithms, TRMM scientists have examined causes of possible bias in the current algorithms and have made resulting improvements. Additional improvements, guided by observational and modeling studies, have been implemented in the V7 rainfall products for the PR (Iguchi et al. 2009, Kozu et al. 2009), TMI (Gopalan et al. 2010), and TMPA (Bolvin et al. 2010). In particular, the V7 data will feature for the first time a TMI algorithm that incorporates information from the PR (Kummerow et al. 2011). In developing a database of cloud profiles for passive microwave retrievals that is based upon the PR-measured profiles, Munchak and Kummerow (2011) presented a retrieval framework based upon optimal estimation theory wherein three parameters describing the raindrop size distribution, ice particle size distribution, and cloud water path are retrieved for each radar profile. In addition to research related to the facility algorithms, work has also progressed on experimental algorithms. Varma and Liu (2010) proposed an algorithm to better classify convective/stratiform rain in those rain events with small area coverage compared to the TMI pixel size. Liao et al. (2009) described a brightband model, having the potential to be used effectively for both radar and radiometer algorithms, allowing the fractional water content to vary along the radius of the particle.

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). T**he TRMM multi-satellite precipitation analysis (TMPA) provides a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at fine scales (0.25° × 0.25° and 3 hourly) (Huffman et al. 2005, 2007).** The TRMM multi-satellite rainfall products are now being used for a variety of important studies, including validation of meteorological reanalyses (Fernandes et al. 2008), hydrologic modeling (Tobin and Bennett 2010), analysis of oceanic precipitation systems (Skok et al. 2009), characterization of monsoon convection (Xu et al. 2009), closure of water budgets (Sheffield et al. 2009), as well as for other hydrometeorological applications (Tao and Barros 2010).

Intercomparison with other satellite-based estimates and ground-based measurements. Given the 13-year long record of TRMM, it is now possible to provide quantitative comparisons between TRMM rainfall data and ground-based measurements on global and regional scales (e.g. Wang and Wolff 2009; Wolff and Fisher 2009; Gourley et al. 2010). The intercomparison efforts are carried out in many countries around world including, for example, Brazil (Franchito et al. 2009), China (Shen et al. 2010), Ethiopia (Hirpa et al. 2010), India (Rahman et al. 2009a), Italy (Villarini 2010), and Korea (Sohn et al. 2010). On the one hand, TRMM data are used for ground radar calibration (Schwaller and Morris, 2011) and to provide high-resolution rainfall information for coarse-resolution rain-gauge networks

(Vila et al. 2009); on the other hand, ground-based data are used to verify TRMM rainfall estimates and algorithms (Wang and Wolff 2008; Wolff and Fisher 2008, 2009; Liao and Meneghini 2009; Fisher and Wolff 2011). The intercomparison and validation of different satellite rainfall estimates, including TRMM products, are performed with the aim of further improving the algorithms (Dinku et al. 2010; Sapiano and Arkin 2009). Global maps of measurement uncertainties (Tian and Peters-Lidard 2010) and component analysis of errors (Tian et al. 2009) helps with assessment of the quality of satellite-based precipitation estimates.

Data assimilation. TRMM has provided major impetus for the data assimilation community **to explore innovative approaches to use rainfall data as well as SST and soil moisture data to improve atmospheric analyses and forecasts**. These new techniques range from rainfall assimilation using column model physics as a weak constraint (Hou et al. 2004; Hou and Zhang 2007) to super-ensemble forecasting techniques (Krishnamurti et al. 2008). Pan et al. (2009) developed a multiscale ensemble filtering system to assimilate TRMM real-time rainfall data into a land-surface model, and found that the ensembles satisfied the requirements for spatial correlation and realism (Pan and Wood 2009). Harrison and Vecchi (2001) concluded that the TMI SSTs are more accurate than NCEP analyses when compared to moored observations. As a result, the TMI SST data have been assimilated in modeling and diagnostic studies (e.g., Klingaman et al. 2008). An improved soil moisture data assimilation system with TRMM data is being developed and tested by Crow and van den Berg (2010). Their results demonstrated that the approach is robust to the presence of autocorrelated observing error, is superior to a classical tuning strategy based on removing the serial autocorrelation in Kalman filtering innovations, and is nearly as accurate as a calibrated Colored Kalman filter.

2.2.4 Applied research

Hydrological/land surface applications. **TRMM-based multi-satellite data are being used as input into hydrological and land surface models, to better understand land-atmosphere interactions on scales of days to years (Rodell et al. 2004), and to improve streamflow prediction (Rahman et al. 2009b; Su et al. 2011).** The high spatial and temporal resolutions of TRMM-based precipitation estimates make TRMM an important source of forcing data for hydrological models (Pan et al. 2010) to simulate hydrologic and hydraulic processes (Beighley et al. 2009). With a combination of TRMM data and a snowmelt model, Bookhagen and Burbank (2010) were able to

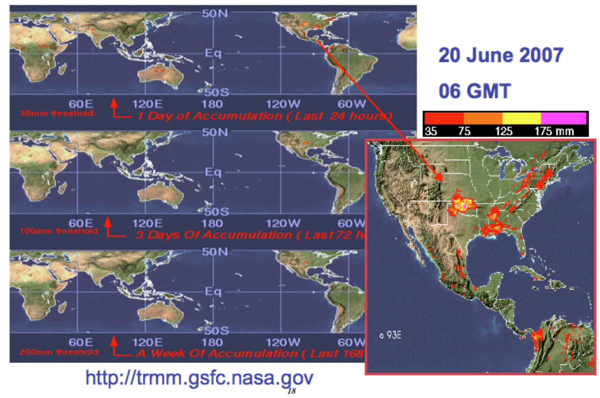

Fig. 6. Example of the real-time heavy rain/flood potential product available from the TRMM web page, http://trmm.gsfc.nasa.gov. The 1-, 3-, and 7-day accumulations are obtained from the real-time TMPA product. Flood potential is assessed based upon the duration and amount of rainfall.

characterize the spatiotemporal distribution of rainfall, snowfall, and evapotranspiration in the Himalayan region, and in turn to quantify their relative contribution to mean river discharge. Providing information on rainfall intensity and duration, TRMM data have been used in the development of a global flood and landslide monitoring system (Fig. 6) (Hong et al. 2006, 2007a, 2007b; Yilmaz et al. 2010b) and in simulating landslide occurrences following an earthquake (Ren et al. 2009).

Model Improvements and Evaluations. With a 13+ year comprehensive dataset, **TRMM data are frequently used to evaluate and improve numerical model simulations and forecasts.** TRMM rainfall data are widely used to evaluate the performance of different numerical models, including the use of global climate models to study monsoon rainfall profiles (Diatta et al. 2010) and to document the rainfall climatology in South America (Da Rocha et al. 2009). TRMM data have been used along with cloud-resolving models to examine along front variability of precipitation in a winter storm (Han et al. 2009), to simulate deep convection during SCSMEX and KWAJEX (Matsui et al. 2009), and to analyze the diurnal cycle of precipitation in the Tropics (Sato et al. 2009). TRMM products were used for an intercomparison of six mesoscale models that simulated rainfall and evapotranspiration associated with a mesoscale convective system over West Africa (Guichard et al. 2010). In addition to model validation, TRMM data also provide a source of information for fine-tuning model forecasts (Voisin et al. 2010) and improving cumulus parameterization schemes (Krishnamurti et al. 2010). Furthermore, Li et al. (2010) found that long-term satellite observations, especially those with multiple sensors such as TRMM, can be very useful in constraining model microphysics. By merging TRMM rainfall data, Yilmaz et al. (2010a) was able to minimize land surface modeling errors and therefore further improve model skill.

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 monitoring climate (Reynolds et al. 2004) and analyzing intraseasonal and seasonal SST variability (Maloney et al. 2008; Kida and Richards 2009). The same data have also been used to study the impact of Saharan dust on tropical and subtropical north Atlantic SSTs (Foltz and McPhaden 2008, Martinez-Avellaneda et al. 2010). Analyzing TMI SST satellite data together with climatological subsurface ocean data, Jansen et al. (2010) suggested that only about one quarter of the heat that is mixed downward by tropical cyclones eventually makes it into the permanent thermocline. Hu and Meehl (2009) found that Atlantic hurricanes have two competing effects on the oceanic meridional overturning circulation and heat transport: hurricane winds increase them while storm precipitation decreases them.

Sensor intercomparisons. TRMM data is regularly used to **improve and validate measurements from other satellite remote sensors (Tran et al. 2005) as well as measurements from ground-based radar measurements (Wang and Wolff 2009).** Yang et al. (2011) used TRMM data to develop a new inter-sensor calibration scheme to estimate the bias of SSM/I monthly precipitation. TRMM observations were also used to verify convective cell occurrence identified by GOES IR observations as a hazard to aviation (Donovan et al. 2008). TRMM SSTs have been compared to measurements from MODIS, AVHRR, and AATSR (Chan and Gao 2005; O'Carroll et al. 2006a, b; Reynolds et al. 2010).

Lightning. LIS data have been inter-compared in detail with ground-based VHF Lightning Mapping Array (LMA) data to create a mapping algorithm that has generated several GOES-R Geostationary Lightning Mapper (GLM) proxy datasets. The proxy datasets have been used in GOES-R GLM risk reduction and lightning Algorithm Working Group (AWG) efforts. Modifications to the LIS clustering algorithm have had a direct impact on the current development of the clustering algorithm for the GLM (Mach et al. 2007). TRMM PR and LIS data were used to verify convective cell occurrence identified by GOES IR observations as a hazard to aviation (Donovan et al. 2008).

Fire detection and monitoring. With channel placements at 3.75 μm and 10.8 μm, **TRMM VIRS has been proven successful at fire detection and monitoring.** Using a multi-year fire dataset generated by Giglio et al. (2003), Giglio (2007) studied the diurnal cycle of detected fires, which exhibit peak burning between 1300 and 1830 LST, with fire activity peaking earlier for heavily forested regions. The fire data is also useful for fire parameterization in global climate models (Pechony and Shindell 2009), as well as for estimation of global biomass burning emissions of organic and black carbon (Vermote et al. 2009).

2.2.5 Operational and applied 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 access through NASA HQ 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 2.2.6) 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, France, India,**

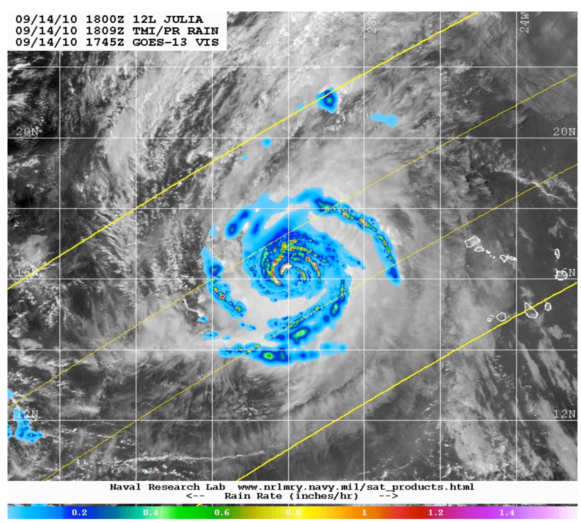

Fig. 7. Example of the real-time TRMM product for Hurricane Julia (2010) on the NRL Tropical Cyclone web page (http://www.nrlmry.navy.mil/ TC.html), showing rain rates from the PR (inner swath) and the TMI (outer swath), overlaid on a concurrent GOES IR image.

Australia, etc. for detecting the location and intensity of tropical cyclones. Over the past five years, JTWC has made an average of nearly 500 tropical cyclone fixes per year using TRMM (K. Payne, personal communication). 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 rain rates into its operational mesoscale 4-DVAR system since 2002 and is planning to assimilate all-sky microwave radiance in its global forecast system. ECMWF has been assimilating rain-affected microwave radiances including TMI data in its 4-DVAR operational forecast system since 2005. 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 its models, which are key elements of its Super Ensemble forecasting system. 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.

2.2.6 National Academy Review

At the request of NASA, the National Academies (NA) completed an assessment of the scientific accomplishments of TRMM and the benefits of extending the TRMM mission (NRC report, 2006). The key findings are summarized in this section.

A key conclusion from the Executive Summary of the NA report was: "*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 research reasons for continuation of TRMM from their viewpoint in Conclusion 4.3 from that report: *"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 operational use 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."*

2.3 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 2 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 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.

Table 2. 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)

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, espe monitoring/forecasting the tracks and intensity of tropical cyclor 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

The TRMM results already described in Section 2.2, valuable though they are, are incomplete in many instances. For example, the thirteen-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 (~2014) will potentially 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

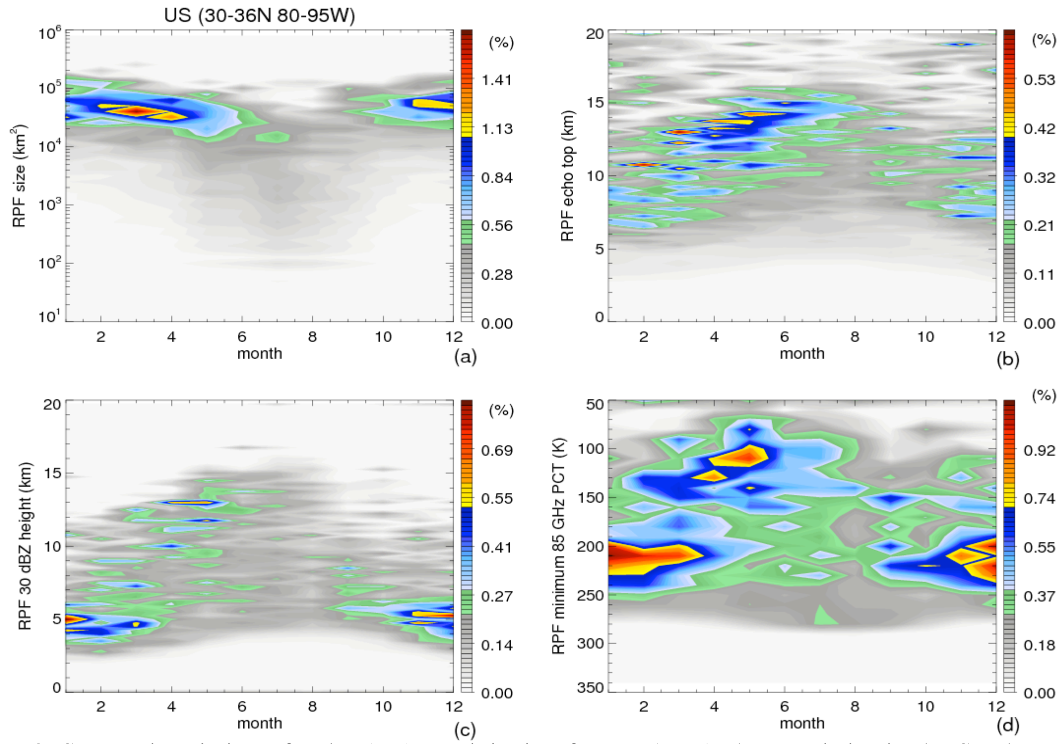

Fig. 8. Seasonal variation of radar (PR) precipitation feature (RPF) characteristics in the Southeastern U. S. including (a) precipitation feature size, (b) echo top, (c) 30-dBZ echo height, and (d) minimum 85-GHz polarization corrected temperature (PCT). Figure is courtesy of Chuntao Liu and Ed Zipser.

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.

2.3.1 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 13 years of data. *Precipitation is an episodic process with small-scale structure, and is therefore much more difficult to characterize and validate than a continuous field such as temperature.* While zonal averages of surface rain over the ocean are now known to within ~10%, the TRMM rainfall algorithms still disagree by relatively larger values on finer scales such as at the resolution of a climate model (~2.5°) (Nesbitt et al. 2004; Adler et al. 2009, Fig. 3). 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. With 13 years of data, analyses such as regional seasonal variations are just now becoming possible (Fig. 8), but will become better defined with additional years of data collection. The TRMM database must be extended to establish the stable statistics needed to define the characteristic features of the tropical hydroclimate. The improved definition long-term means and variability 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

2.3.2 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?

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 13-year TRMM record that now exists includes the later stages of the major 1997-1998 El Niño, the weaker 2002-2003, 2004-2005, and 2006-2007 events, and the most recent 2009-2010 event. The differences between these events illustrate their variability in intensity and character from event to event. While these events 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 2011 and 2015. 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.

2.3.3 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, 13-year TRMM record is being used to assess the accuracy of variations and trends in the 33-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.

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.

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

Science Question 5: 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?

The data assimilation and NWP community is still 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 addition of CloudSat and CALIPSO in 2006 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, the TRMM PR will have a critical role in precipitation forecast validation.

Continuation of TRMM will stimulate advances in the assimilation of precipitation data in NWP models to improve forecasts.

2.3.5 Tropical cyclone processes

Science Question 6: What are the primary physical processes relating inner-core convection to tropical cyclone intensity change?

Science Question 7: 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 precipitation structure of these convective systems and it has already provided more data on the vertical structure of precipitation in tropical cyclones than a half 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 (Kelley et al. 2004). 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 relatively short TRMM record is just beginning to sample an adequate variety of extreme events. For example, it has only recently become possible to characterize the global distribution of extreme characteristics of tropical cyclones using TRMM (Fig. 9). 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.

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.

2.3.6 Characteristics of convective systems

Science Question 8. 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?

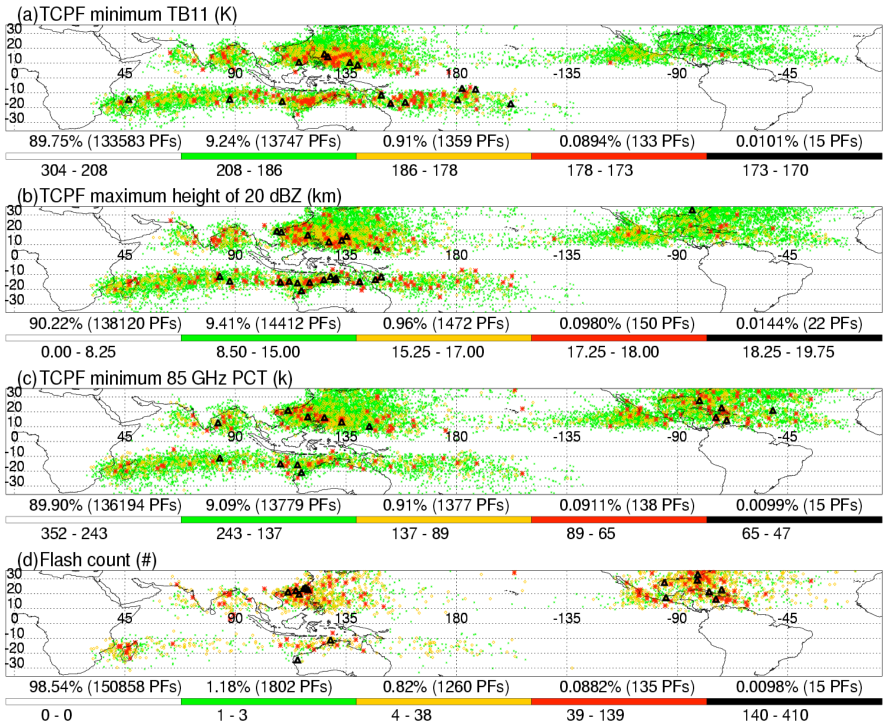

Fig. 9. Locations of deep convection events in TCs categorized by (a) minimum T_{B11} from VIRS, (b) maximum height of 20 dBZ echo from PR, (c) minimum 85 GHz PCT from TMI, (d) and flash count from LIS. Rarity of the events are represented with green dot (~top 2% for flash count and ~top 10% for all other parameters), orange dot (~top 1 %), red star (~top 0.1%), and black triangle (~top 0.01%) symbols from TC precipitation features from 1998 to 2009. Figure courtesy of Haiyan Jiang.

Science Question 9. 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 13 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 (Fig. 10). However, the limited time record still 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 the tropics. 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. 10). 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),

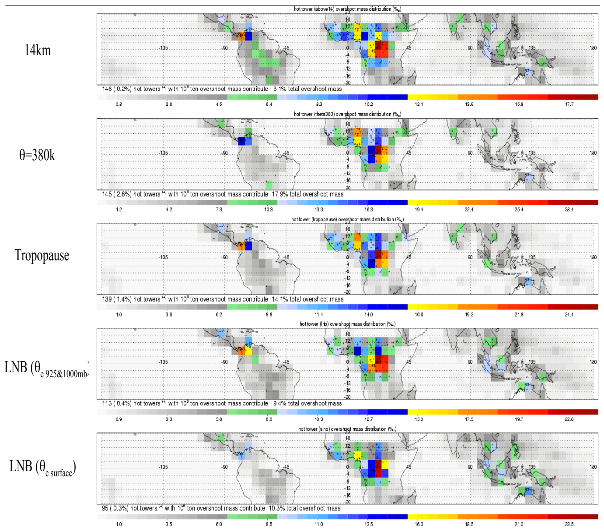

Fig. 10. Fractional contribution (parts per thousand) of each 5° square to total mass of precipitating ice from hot towers in the tropical tropopause layer for 5 years of TRMM PR data. Five different reference levels are used, with average height ranging from 14.0 – 16.8 km. For any definition of reference level, the dominance of land over ocean, and of tropical Africa over South America and Indonesia is clear.

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 cleaner.)

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

2.3.7 Hydrologic cycle over land

Science Question 10: How are hydrologic fluxes and states such as runoff, evapotranspiration, soil moisture, and groundwater recharge affected by changing precipitation patterns?

Science Question 11: Is the frequency of extreme hydrologic events such as droughts and floods changing?

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.

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. Analysis by Fekete et al. (2004) demonstrated a significant amplification of uncertainty in using precipitation fields from commonly applied global precipitation products (6 products, 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 2014, 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 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.

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

2.3.8 Impacts of humans on precipitation

Science Question 12: What is the quantitative aerosol-precipitation relation on a global or regional basis and the relative impact of pollution on those relations?

Science Question 13: 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 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 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, 2008) 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. 11) 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 TRMM precipitation record will be critical for monitoring impacts of deforestation in the Amazon and around the world.

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 compared to less direct techniques; and (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.

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.

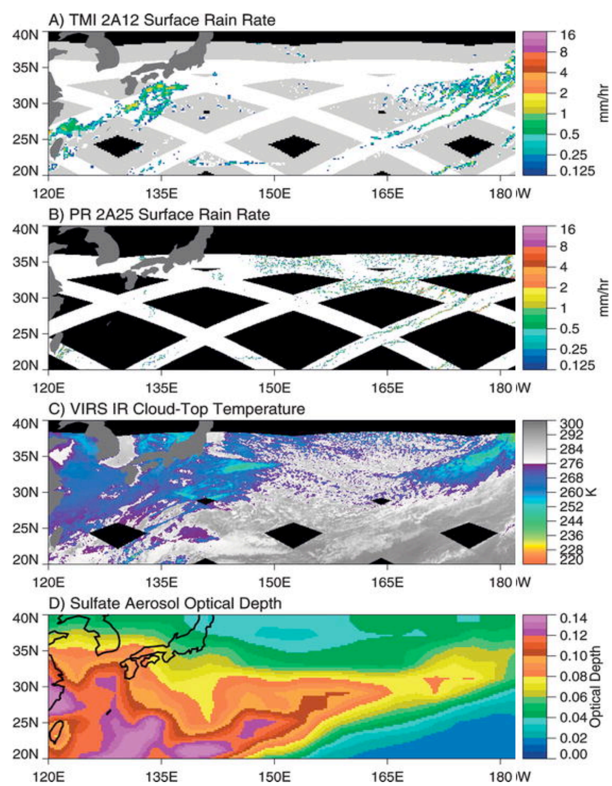

Fig. 11. (a) TMI 2A12 rainfall, (b) PR 2A25 rainfall, (c) VIRS cloud-top temperatures, and (d) model-derived sulfate aerosol optical depth for 1 Feb 2000. The nonraining portions of the TMI scan outside of the PR scan in (a) are gray; nonraining TMI pixels within the PR scan are white. (From Berg et al. 2006)

2.3.9 Lightning

Science Question 14: What are the characteristics of lightning and precipitation at the storm cell scale, and how does the coarser TRMM sampling impact retrieved lightning and precipitation diagnostics?

Science Question 15: Is there any evidence for a change in behavior of global tropical and/or regional lightning flash frequency concurrent with other climate markers or hypothesized manifestations of climate change (i.e., increased tropical cyclone frequency/intensity)?

Science Question 16: What are the precipitation properties, controlling environmental factors, and lightning characteristics of extreme storms?

Since convective precipitation and lightning are generated predominantly on the scale of individual storm cells, it is important to quantify behavior at this scale in order to study the potential impacts (e.g., aliasing) on TRMM lightning and precipitation diagnostics retrieved at larger space and time scales. A possible methodology could include a reprocessing of the University of Utah precipitation feature database to isolate individual convective cells and attendant lightning flash characteristics. Such a convective-scale database may provide information on assumptions about the vertical distributions (size, shape, phase) of hydrometeors and perhaps provide useful corrections of retrieval algorithm bias in hydrometeor/precipitation profile diagnosis, particularly over land where lightning is the most concentrated, ice processes are the most active, and physically-based passive-microwave retrieval algorithms rely heavily on the scattering contribution from ice. The TRMM information may provide metrics for regionally tuning precipitation retrieval algorithms over land by combining lightning input from total lightning mapping sensors flying on satellite platforms such as TRMM, the Brazilian GPM constellation satellite and/or the NOAA GOES-R GLM.

LIS has been in orbit for approximately 13 years and the mission is projected to continue to ~2014 (16 years). The extension of the lightning dataset to 16 years will provide a more robust means to examine feedbacks between the slowly varying climate system (e.g., increasing temperature, humidity, etc.) and lightning activity, which serves as an excellent proxy for convective frequency and intensity. LIS data will allow an assessment of changes in extreme weather and will provide validation information for model simulations of convective frequency and intensity.

TRMM data will establish relationships between lightning intensity/frequency and the characteristics of convective systems and their environment.

2.3.10 TRMM combined with new, unique observations

Science Question 17: 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 18: 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]

Science Question 19: 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 information that would come from an overlap of TRMM with the GPM core satellite. 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 dual-frequency radar (DPR) as the calibration reference. To provide better continuity between the TRMM and GPM eras, a period of overlap (at least 6 months to 1 year) of the PR and DPR is required.

Another obvious example 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." 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

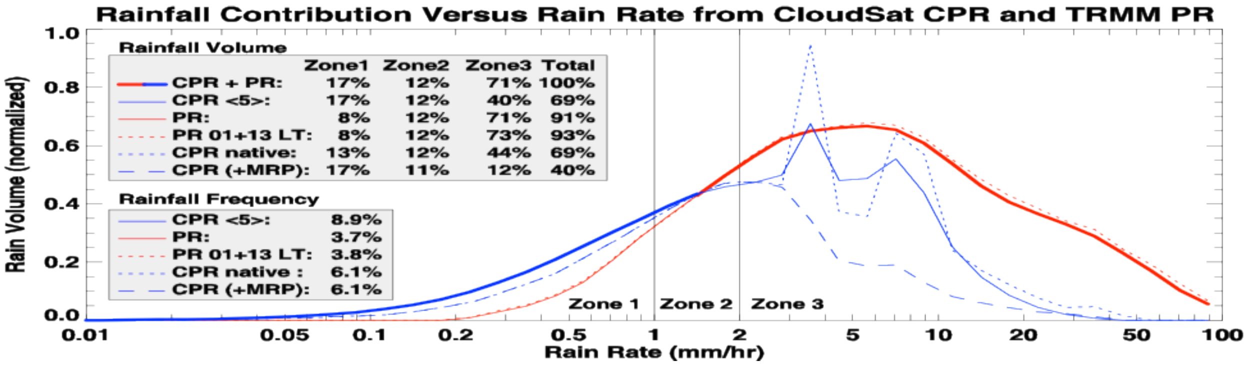

Fig. 12: The distribution of the total rain volume from the CPR and PR as a function of rainfall intensity over tropical and subtropical oceans (35ºS to 35ºN) for the period from June 2006 through February 2009. The range of values within each bin is based on the log of the rain rates. The number of observations within each bin is multiplied by the rain rate to indicate the relative contribution of both the lowest and highest rain rates in the distribution to the total rainfall. The complete PR distribution (solid red line) is shown along with the PR estimates subsampled at the local CloudSat observing times (dotted red line). The CPR estimates averaged over 5 adjacent pixels (solid blue line) are shown along with the native resolution CRP estimates (dotted blue line) and with the estimates exceeding the maximum retrievable precipitation rate (MRP) removed (dashed blue line). Comparison of the thick blue line in zones 1 and 2 to the thin red line highlights the light rain seen by the highly sensitive CloudSat radar but not observed by the lower sensitivity TRMM PR. Image courtesy of Wes Berg.

precipitation that has been below TRMM's measurement threshold (Fig. 12). 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.

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 TMPA, SSTs from TMI, 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 (Lau and Kim 2007a, 2007b; Sun et al. 2008; Braun 2010a, 2010b; Sippel et al. 2011). Data from multiple years suggest that dust slightly reduces SSTs in the tropical Atlantic; that hurricanes often form either at the leading edge or just trailing major dust outbreaks; that there is considerable variability from year to year; and that the relationship between Saharan air layer characteristics and storm evolution remains uncertain. Since MODIS data from both Terra and Aqua are required to adequately resolve the daily evolution of the dust outbreaks, the analysis is currently only available for 2002-2010. 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.

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, NAMMA, and GRIP. TRMM will also provide critical information for the upcoming Hurricane and Severe Storm Sentinel (Earth Venture-1) series of hurricane field experiments in 2012-2014.

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.

2.4 Statement of Work

The TRMM Data/Analysis (DA) budget comprises two parts: a precipitation component (TRMM/GPM) managed at Goddard and a lightning component (LIS) managed at Marshall. The following sections describe these separate components.

2.4.1 TRMM/GPM

As mentioned in section 2.1, since 2003, TRMM and GPM science activities have been merged under the umbrella of PMM. The TRMM/GPM component of the DA budget supports activities related to both TRMM and GPM in three specific overlapping science activities: 1) PMM project management and science, 2) GV operational and science activities; and 3) TRMM algorithm maintenance and GPM algorithm development and implementation. Project management and science are described in the budget narrative in section 3.2.2.

The TRMM GV program utilizes data from four primary GV sites (see section 2.1.5): Kwajalein, Melbourne, Houston, and Darwin (data collection here ended in 2003). Kwajalein, which operates a dual-polarization radar, represents the only over-ocean GV site, which makes it critical for evaluation and validation of over-ocean precipitation retrieval algorithms. Its remote location, however, increases the costs of operating and maintaining the site. The TRMM mission funds military personnel at Kwajalein to operate and maintain the radar and rain gauges located on nearby islands. Goddard scientists have made, and will continue to make, regular trips to Kwajalein to calibrate the radar and provide engineering support. For Melbourne, the TRMM mission will provide for maintenance of a high-quality rain gauge network near the Melbourne radar site. Data from these sites have been critical to the ongoing evaluations of TRMM Version 7 algorithms and are expected to continue operations into the GPM mission phase to support GPM product evaluation. No support is needed for the Houston site.

The NPOL radar is a critical facility instrument for the PMM program. After the completion of a new antenna in 2010, it is positioned to become one of the premier radar facilities in the country. NPOL is regularly deployed in the field for precipitation-related field campaigns. The PMM program will provide routine engineering and quality assurance support for NPOL.

A key part of the TRMM GV program is the routine production of operational radar and rain gauge products. While significant efforts have been made toward automation, the process remains dependent on a very manually intensive part of the data processing, that is, the editing and quality control of the radar and gauge data. The PMM program will continue processing of all GV data, posting of data to online archives, maintenance and development of code, and provision of IT support.

The project supports both core-product TRMM algorithm maintenance and GPM algorithm development and implementation for delivery to the PPS. A key objective of TRMM was to use data from the PR to enhance the microwave-only precipitation retrievals, referred to as a “radar-enhanced” product. As a result of ROSES science and algorithm funding, with additional support from the TRMM DA budget, TRMM will be implementing a new version of its algorithms, Version 7, in 2011 that will feature for the first time a microwave algorithm that incorporates information from the PR. As described in Appendix A, the current (Version 6) microwave algorithm uses a database of hydrometeor mass profiles generated by cloud-resolving numerical models. In V7, the database will be generated primarily by the PR, thereby providing a much more realistic constraint on the precipitation retrievals. An improved PR algorithm will also be implemented that is expected to correct a negative bias seen in the radar reflectivities produced by the V6 algorithm. The new code has been delivered to the PPS and is currently being tested and evaluated. In 2011, researchers in the PPS office, at Goddard (primarily the GV group), and among the science team will participate in an evaluation of a 2-year dataset to ensure that any errors or inconsistencies are caught prior to a full reprocessing of the TRMM 13+ year dataset. Reprocessing and release of the V7 products is expected to occur in May of 2011.

The implementation of the V7 TRMM algorithms represents only a starting point for the GPM algorithms that must be implemented and tested for delivery to the PPS by 2012. The GPM algorithms must account for two radar frequencies instead of one, and must incorporate higher frequency microwave channels that are not part of TMI. To ensure that advanced algorithms are in place by 2012, the PMM office has established four algorithm implementation teams: a satellite inter-calibration team, a dual-frequency radar team, a combined radar/radiometer team, and a radar-enhanced radiometer algorithm team. These teams are responsible for defining, developing, implementing, and delivering the “at launch” GPM algorithms to the PPS using experience from TRMM and incorporating new information from field campaigns.

2.4.2 LIS

MSFC’s main activity under LIS funding will be the continued monitoring of LIS instrument health and continued production of LIS products at the LIS Science Computing Facility through 2011-2013. In addition to this data processing function, LIS science activities will be centered on seven different research areas. These include:

<u>Lightning and Precipitation.</u> Reprocessing of the Precipitation Feature Database to focus on cell-scale phenomena, isolating individual convective cells and attendant lightning flash characteristics, microphysical properties, and multi-frequency brightness temperatures. Passive microwave retrievals of precipitation will be evaluated in the context of the database analysis (Leroy and Petersen, 2011).

<u>Lightning Climatology</u>. Examination of long-term trends in lightning activity through extension of the lightning climatology to the full period of TRMM data collection, monitoring changes in the global electric circuit (Carnegie Curve), removal of bias related to orbit boost, and an increase of the horizontal resolution of the analysis.

Extreme Storms. Examination of high-flash-rate storms and the role of erroneous flash detections. Estimation of instantaneous, monthly, and seasonal precipitation properties associated with extreme weather events over the CONUS and relationship to environmental factors controlling lightning and precipitation. Also, examinations of the ratio of intracloud to cloud-to-ground lightning in extreme/severe storms.

Lightning Chemistry. Improve lightning NO_x estimates in the Community Multiscale Air Quality (CMAQ) regional air quality model and GEOS-Chem models. Continue deployment of a ground-based electric field change network, and relate LIS optical measurement to flash energetics. Further test and optimize the ground flash fraction retrieval algorithm for atmospheric chemistry application.

Applied Research. Develop Level-1 & Level-2 GLM proxy data to test GLM Lightning Cluster Filter Algorithm performance, and to test the performance of several other lightning-related GOES-R Risk Reduction algorithms under development. Conduct extreme value analysis of LIS data to see when and where maximum lightning rates can be expected for GLM.

New Operational Uses of LIS data. Optimize the ground flash fraction algorithm to create, for the first time, separate geographical distributions of the ground and cloud flash density. Also, for the first time, create routine *Modernized Carnegie Curve* products that characterize the changes in the global electric circuit.

Analysis of Oceanic Lightning. Examination of land/ocean differences in lightning, the key environmental differences, and associated microphysical properties.

Lightning Validation. A network of ground based sensors known as the Hunstville Alabama Marx Meter Array (HAMMA) has recently been developed to measure the energetics of lightning activity and to validate space-based lightning observations. This network will be required for the quantitative evaluation of GLM performance. It is also valuable for determining how to convert LIS measured optical energies into equivalent lightning flash energy.

3. TECHNICAL SECTION

3.1 Technical Status

3.1.1 TRMM spacecraft operations status

In the last two years, in addition to mission operations activities, the Flight Operations Team (FOT) has been supporting the validation and verification of the end-to-end technical refresh of the entire TRMM Operations Control Center ground system elements. This ground system reengineering activity has been in response to new IT Security policies and requirements that included the availability of a full operational backup facility for operations. The security enhancements and changes have greatly improved the TRMM ground system security posture and system reliability for the duration of the TRMM mission. The ground system currently has a much more secured operational network and a more reliable automation system through hardware and software changes that were part of the proposed budget in FY09-10. A technology refreshed level-zero processing system (PACOR) was also put in place to replace a limited-supported system in FY10. The old system shared operations and data processing with the Hubble Space Telescope (HST) and a decision was made to decouple the dependency and coexistence with the HST segment due to changes in HST processing requirements that would have increased the cost of TRMM data processing. The new PACOR has improved automation capabilities and security features, and it will be more maintainable for the duration of the TRMM mission. The new PACOR also operates in a “lights-out” mode of operation for eight hours a day, five days a week. The system reliability is such that science data recovery levels have been maintained since transition to its unmanned mode of operations after regular hours and on weekends. In FY10, the old legacy telemetry and command system (TPOCC) that was used at the backup facility was decommissioned and removed from operations. The TPOCC was replaced with an upgraded system that meets current IT security requirements and is much more reliable and maintainable than the old system. However, there is still need for some necessary upgrading of the mission planning and Space Network (SN) scheduling systems with new hardware, software, and operating systems. This is necessary to be in compliance with the SN scheduling system requirements. The upgrades are designed to be maintained and supported beyond 2014, thus reducing security vulnerabilities, as well as having a more reliable mission planning and scheduling system. Some of the other ground system refresh and upgrade efforts are expected to be completed by the end FY11. This will assure safe operations of the TRMM mission beyond 2014, if necessary to continue the mission, for data continuity purposes with GPM.

In general, TRMM Mission Operations personnel successfully planned, managed and executed an average of 6,309 spacecraft contacts, 7 drag/make-up and 16 attitude maneuvers per year. Automation efforts and other cost saving strategies have helped maintain high data capture rates despite significant decreases in flight operations personnel resulting from budget reductions in years prior to and including 2009 and 2010. Table 3 shows the operations reduction in personnel while maintaining the same overall level of data capture for the last five years.

Table 3. Reductions in operations manpower and continued high data capture rate.

Year	Ops FTE	Data Capture %
2006	10	99.943
2007	9	99.953
2008	8	99.686
2009	8	99.785
2010	7	99.840

3.1.2 TRMM spacecraft status

The TRMM spacecraft is in excellent condition after thirteen years in orbit. There have been no subsystem-specific issues in the last two years. An assessment of mission lifetime expectancy based upon remaining fuel is in Appendix E. An independent technical assessment of the 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 is a high level summary from the 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 and it is extensively supported by the power subsystem branch (Code 563) at GSFC.

In summary, in terms of TRMM mission extension impacting spacecraft systems, the "*change in risk is minimal.*" As previously determined by the Deily evaluation and based on current extensive analysis by the TRMM subsystem engineering staff*: "There are presently no subsystem-specific issues that will limit the lifetime of any major spacecraft subsystem or component in the next few years*."

3.1.3 Status of TRMM instruments

Precipitation Radar (PR). The TRMM PR has operated nearly 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. 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. The only problem to occur with the PR was a failure in May 2009 of the Frequency Converter and Intermediate Frequency unit and the System Control and Data Processing unit. However, the radar was built with redundant components and PR operations were restored in June 2009 after switching from the "A side" to the "B side" units. **Therefore, because there is no known component limiting its life, the PR is projected as highly probable to continue operating nominally for the next four years.**

TRMM Microwave Imager (TMI). 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, two are still operating with lifetimes so far of 14 and 11 years. Four other SSM/I's were operating at 7, 9, 11 and 17 years when the spacecraft failed in one case and was turned off in the other cases. **No SSM/I mission was ended because of instrument failure. Thus, there is a good probability that the TMI will operate successfully for several more years.**

Visible and InfraRed Scanner (VIRS). 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 continues to provide full functionality. Recent results, employing the Deep Convective Cloud methodology (Doelling et al., 2004), indicate that LIS sensitivity and performance continue 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.

3.1.4 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 approximately 1.2 kg of propellant each time. As of February 2, 2011, TRMM is estimated to have approximately 93 kg of propellant remaining**.** Based only on station-keeping fuel availability, *TRMM has the potential to stay on station doing science until late 2014*. 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 5 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 8719.14, "NASA Policy for Limiting Orbital Debris Generation" and Orbital Debris Mitigation under NSS 1740.14. The ESMO Project updates 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, UARS in December of 2005, TOMS in December of 2006 and ICESat in July 2010 by the current Mission Operations Director.

3.1.5 Conjunction assessment/collision avoidance

As required by NPR 8715.6a, the ESMO Project has established a routine conjunction assessment (CA) process for NASA robotic missions with the Department of Defense (DoD) U.S. Strategic Command (USSTRATCOM) as documented in the "DoD/NASA Memorandum of Agreement for Support to NASA Spaceflight Operations". The GSFC Space Systems Protection Mission Support Office (Code 590.1) provides the CA service. Twenty-seven NASA robotic missions including eleven Earth Science missions (Aqua, CALIPSO, PARASOL, Aura, Landsat-7, Landsat-5, EO-1, SAC-C, Terra, **TRMM**, and ICESat) are being routinely screened against the USSTRATCOM catalog of resident space objects three times a week and more frequently if a high-risk close approach is predicted. Since the process was implemented in January 2005, there have been 9 conjunctions requiring risk mitigation maneuvers to be performed by NASA Earth Science spacecraft, including two for Terra (Oct 2005 and June 2007) and one for Aura (June 2008). Debris from the Chinese Anti-Satellite test in January 2007 led to a measurable increase in the number of predicted CA events for the Earth Science satellites. Terra had to perform its second risk mitigation maneuver in June 2007 to avoid Chinese debris. The recent (February 10, 2009) collision between a Russian satellite and a U.S. Iridium satellite has increased the need to protect and respond to any probability of collision, as it will have a long-term impact on the satellites in EOS orbits. The cost for the CA service is shared among multiple missions.

3.2 Budget

The TRMM mission requests budget consistent with its guideline budget determined from the 2013 Program Planning and Budget Execution process.

3.2.1 Mission operations in-guideline budget narrative

The mission operations budget is comprised of two components: Flight operations and ground system infrastructure sustaining engineering support. The proposed budget supports the necessary levels of flight operations staff to safely operate the TRMM spacecraft and maintain the current levels of science data recovery. The TRMM flight operations staff level was reduced between FY2005 and FY2010 while taking budget cuts in FY 2008 and 2009 (approximately $400,000 each FY), and in 2010 (approximately $175,00). These reductions forced a slowdown of the ground system refresh and IT security efforts under the ground system infrastructure engineering support. The ground system refresh and IT security were absolutely necessary to be in compliance with existing NPR-2810A security requirements. The proposed budget for mission operations includes preparation activities for decommissioning activities to possibly start in FY12. However, there is a chance that fuel could last into 2014 and, perhaps optimistically, into 2015. The uncertainty lies in the amount of propellant currently remaining and the rate that it will get consumed due to increasing solar activity, both of which appear to be fairly uncertain (Appendix E). So the proposed budget includes planning for these later years just in case the mission is extended to perform data correlation with GPM. The proposed budget also includes some post-decommissioning activities necessary to close out the ground system and possible reprocessing of data by PACOR within six months after completion of spacecraft passivation. This planning is based on previous mission decommissioning experiences by the ESMO Project, the latest being ICESat in July 2010.

In general, it is absolutely necessary to maintain the current levels of flight operations personnel, as well as the ground system infrastructure to minimize any impacts to ongoing mission operations activities and science data recovery. While a significant effort has been made in reducing flight operations staff, the ever-increasing and changing Federal and NASA security requirements have added to the system administration and licensing costs. This has required the reallocation of those savings and of additional funds for the remaining time of the mission to stay current with the latest security policies and measures. Consequently, proposed budget levels have to be maintained to meet those new requirements. TRMM decommissioning activities will also require certain high levels of technical knowledge and expertise that can be lost due to budget cuts with further reduction in flight operations personnel. It should also be considered that JAXA might want to perform engineering tests and calibrations of the radar in preparation for GPM that will require direct operations support and other engineering support from AETD/Code 500.

3.2.2 Data analysis in-guideline budget narrative

Since 2003, TRMM no longer has a separate science team and TRMM-only data analysis (DA) budget. 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. The DA budget combines activities for TRMM and GPM related to project management, project science, algorithm development, and GV. *Although total PMM mission-directed science funding (non-ROSES) is expected to increase, the TRMM portion of that funding will decrease from the current year through the 2012-15 period.* Budgets for LIS operations, data processing, and science at 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.

The TRMM/GPM DA budget comprises three components: Project management and science, algorithm development and maintenance, and GV. Project management and science funding includes business and administrative activities used to accomplish TRMM and GPM mission objectives and TRMM project scientist support. Algorithm maintenance and development support contributes to TRMM V7 algorithm development, testing and maintenance, as well as GPM at-launch algorithm development support. GV site support includes infrastructure support at Kwajalein and Melbourne, instrumentation, and production of validation products. TRMM DA also includes LIS operations, data processing, and science support. Science data processing (TSDIS) operations have been transferred to the PPS (under separate budget) and are performed at no cost to the PMM program. This support is listed as in-kind support in the budget pages under the PPS. The transition to the PPS occurred in June of 2008. This transition from TSDIS to PPS has allowed for efficient continuation of production of precipitation products going from TRMM to GPM in a cost effective manner.

Project science support includes project scientist labor and research support for the TRMM Project Scientist, PMM grant support, and program office support. The program office provides support for PMM working groups, algorithm science team meetings, CEOS related activities, and education and public outreach. Finally, funding is provided for travel required for program-related activities.

The algorithm maintenance and development portion of the budget includes PMM algorithm team support to ensure delivery and implementation of algorithms developed through the PMM ROSES-funded science team efforts. In the short term, support is provided for implementation, testing, and evaluation of V7 of the TRMM algorithms. In the long term is support of algorithm development for the first version of the GPM algorithms, including development of core microwave-only and combined (radar and microwave) algorithms, multi-satellite products, and satellite simulators. Since GPM requires interaction with a broad array of international partners (including the French-Indian Megha-Tropiques satellite), support is planned for international GV collaboration-building activities.

The third precipitation-related part of the DA budget is GV site support, instrumentation, and validation products. GV site support includes engineering and maintenance support for the Kwajalein Atoll and Melbourne, FL, GV sites. The mission funds engineering support and quality assurance for the NPOL radar and procurement and/or deployment of rain gauges, profilers, and disdrometers at GV sites. The largest portion of the GV budget is related to the production of the operational GV products at all the active radar sites (Kwajelein, Melbourne, and Houston). While efforts are being made to automate as much of this process as possible, the quality control portion of production is very manually intensive. Reductions in manpower in the GV program were made in 2009 so that only core operational product generation is now supported.

The LIS contribution to TRMM Project Management is small, consisting of support to the TRMM project office for programmatic activities (e.g., budget inputs, reports, reviews). Similarly, the LIS budget associated with TRMM Mission Operations is also small. It supports monitoring of LIS instrument health, providing instrument command requests to the GSFC FOT, and assuring the proper transfer of raw level-0 LIS data from the GSFC MOC to the LIS Science Computing Facility located at the National Space Science and Technology Center (NSSTC).

The majority of the LIS budget supports science and data analysis. This encompasses the management and execution of both LIS data processing and extended science mission research activities. The LIS data processing includes the routine generation of LIS products, quality control, associated archival and distribution services, and maintenance of LIS processing algorithms and code. The GHRC manages the archival/distribution services for LIS data with support it receives from the LIS budget.

The extended science mission research efforts for LIS support highly focused investigations with an emphasis toward the development of *new products* or improvements to existing products that lead to advancing scientific understanding. The tasks and expected results of these efforts will benefit both current TRMM science studies as well as future missions/investigations, and are discussed in detail in the LIS statement of work (see section 2.4.2). Also, LIS directly facilitates risk reduction and algorithm development for the future NOAA GOES-R GLM. NASA is heavily involved in the GOES program. It manages the development of all space segment components including all instruments and satellites.

The LIS data processing and extended science mission research activities are conducted with both civil service and contractor support. The contractor support is provided through cooperative agreements, primarily with the University of Alabama in Huntsville (UAH) and the Universities Space Research Association (USRA). In the LIS budget, contractor WYE's are not explicitly shown due to how MSFC manages and tracks cooperative agreements (contractor costs are rolled into the procurement line). The LIS budget includes 2 FTE's for civil servant support (shown) and the equivalent of 7 WYE's (not explicitly shown) for contractor support. The main portion of the WYE budget (5 WYE's) is for supporting LIS data processing and the development of new products and/or improvements to existing products. In addition, 4 full-time graduate students are actively supporting these activities, accounting for 2 WYE's. Finally, in addition to the labor, there are some small costs associated with recurring procurements and TRMM related travel.

PMM science team funding under ROSES is listed as in-kind support. A new science team was selected in FY2010 and the science team is currently in its first year of support. Although algorithm development is accomplished under ROSES, it is typically done as part of a broader research project under a number of investigators. The portion of their work dedicated to algorithm development versus general science is difficult to estimate. Consequently, the full ROSES funding is listed as in-kind support. PPS in-kind support represents the fraction of the total PPS budget that is estimated to support TRMM data processing.

Appendix A: TRMM Mission Data Product Summary

All TRMM products start from Dec. 1997 (duration is 11+ 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. User information is listed at the end of this appendix by grouping: NASA, NOAA, DOD, international weather agencies (IWA), other U. S. government (OUSG), and private industry or other (PIO). All acronyms are listed in Appendix C.

Data is available from the following sites:
GSFC DISC: http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&project=TRMM
MSFC/GHRC: http://lightning.nsstc.nasa.gov/data/index.html#Order
PPS: https://storm-pps.gsfc.nasa.gov/storm/html/Storm.html

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 1R**eal-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.	NASA NOAA DOD IWA PIO	GSFC/DISC

			Geolocation is 2 byte integer for lat and for long rather than 4 byte as in production.		
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.	NASA NOAA DOD IWA	PPS
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.		PPS
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 DOD IWA	PPS

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	PPS

Level 3 Satellite Standard Products

Name	Product No.	Instrument	Product Description	Users	Access
TMI monthly rain	3A11	TMI	Monthly 5º 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.		PPS
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.		PPS
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.	NASA	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, 0.25º resolution.	NASA	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.	BOM	PPS
IR precipitation	3B41rt	PR, TMI AMSR SSM/I AMSU GEO-IR	3-hourly IR precipitation data adjusted by radiometer data at 0.25° resolution.	BOM	PPS

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	NASA NOAA/ CPC NRL JMA BOM India OUSG PIO	PPS

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

Description of Primary TRMM Standard Rain Algorithms/Products (Version 6)

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 5º x 5º 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 B – Budget

Budget pages are included as a separate file Appendix_B_TRMM_SR.xls

Appendix C – Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
AETD	Applied Engineering & Technology Directorate
AGU	American Geophysical Union
AIRS	Atmospheric Infrared Sounder
AMMA	African Multi-Disciplinary Monsoon Analysis
AMPR	Advanced microwave precipitation radiometer
AMS	American Meteorological Society
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
ARC	Active Radar Calibrator
ARM-CART	Atmospheric Radiation Measurement-Cloud And Radiation Testbed
AVHRR	Advanced Very High Resolution Radiometer
AWC	Aviation Weather Center
AWG	Algorithm Working Group
BOM	Bureau of Meteorology (Australia)
C&DH	Command and Data Handling
CA	Conjunction assessment/collision avoidance
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMEX	Convection and Moisture Experiment
CARE	Center for Atmospheric Research Experiments
CCD	Charged-coupled device
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and Earth Radiant Energy System
CLIVAR	Climate Variability and Predictability Research
CloudSat	Cloud Satellite
CMAP	CPC Merged Analysis of Precipitation
CMAQ	Community Multiscale Air Quality (model)
CMORPH	CPC MORPHed precipitation
CONUS	Continental United States
COSMIR	Conical Scanning Millimeter-wave Imaging Radiometer
CPC	Climate Prediction Center
CPF	Cloud and Precipitation Feature
CPR	CloudSat Profiling Radar
CSH	Convective-Stratiform Heating (algorithm)
DA	Data Analysis
DAAC	Distributed Active Archive Center
DISC	Data and Information Services Center
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DORADE	DOppler RAdar Data Exchange (format)
DP	Dual Polarization/Polarimetric
DPR	Dual-frequency Precipitation Radar
DSD	Drop Size Distribution
DVAR	Dimensional Variation Assimilation System
ECMWF	European Centre for Medium-Range Weather Forecasts
EMC	Environmental Modeling Center
ENSO	El Niño-Southern Oscillation
EOL	End of life
EOS	Earth Observing System
E/PO	Education and Public Outreach

ERA40	40-year European Re-Analysis
ERBS	Earth Radiation Budget Satellite
ESA	European Space Agency
ESMO	Earth Science Mission Operations
FOT	Flight Operations Team
FSU	Florida State University
FTE	Full-Time Equivalent
GCM	Global Circulation Model
GEOS	Goddard Earth Observing System (model)
GES-DISC	Goddard Earth Science-Data and Information Services Center
GEWEX	Global Energy and Water Cycle Experiment
GHRC	Global Hydrology Resource Center
Giovanni	GES-DISC Interactive Online Visualization and ANalysis Infrastructure
GIS	Geographic Information System
GLDAS	Global Land Data Assimilation System
GLM	Global Lightning Mapper
GMAO	Global Modeling and Assimilation Office
GMI	GPM Microwave Imager
GOES	Geostationary Operational Environmental Satellites
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Measurement
GPROF	Goddard PROFiling (algorithm)
GRIP	Genesis and Rapid Intensity Processes
GSFC	Goddard Space Flight Center
GV	Ground Validation
HAMMA	Huntsville Alabama Marx Meter Array
HDF	Hierarchical Data Format
HIWRAP	High-altitude Wind and Rain Profiling Radar
HMT	HydroMeteorological Testbed
HQ	Headquarters
HST	Hubble Space Telescope
IAG	Instituto Astronomico e Geofisico
IDL	Interactive Data Language
IFOV	Instantaneous field of view
IR	Infrared
IT	Information Technology
ITCZ	Inter-Tropical Convergence Zone
IWA	International weather agencies
JAXA	Japan Aerospace Exploration Agency
JCSDA	Joint Center for Satellite Data Assimilation
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Center
KPOL	Kwajalein POLarimetric (radar)
KWAJEX	Kwajalein Experiment
LDAS	Land Data Assimilation System
LIS	Lightning Imaging Sensor
LMA	Lightning Mapping Array
MC3E	Midlatitude Continental Convective Clouds Experiment

MJO	Madden-Julian Oscillation
MO	Mission Operations
MOC	Mission Operations Center
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	Multi-satellite Precipitation Analysis
MRP	Maximum Retrievable Precipitation (rate)
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
NCAR	National Center for Atmospheric Research
NCEP	National Centers of Environmental Prediction
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
NOX	Nitrogen Oxides
NPISO	Northward Propagating Intra-Seasonal Oscillation
NPOL	NASA POLarimetric (radar)
NPR	NASA Procedural Requirements
NRC	National Research Council
NRL	Naval Research Laboratory
NSS	National Security Systems
NSSTC	National Space Science and Technology Center
NWP	Numerical Weather Prediction
NWS	National Weather Service
OCC	Operations Control Center
OLR	Outgoing Longwave Radiation
OTD	Optical Transient Detector
OUSG	Other U. S. government
PACOR	Packet Processor
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PCT	Polarization Corrected Temperature
PDF	Probability Distribution Function
PERSIANN	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
PF	Precipitation Feature
PI	Principle Investigator
PIO	Private industry or other
PMM	Precipitation Measurement Missions
PPS	Precipitation Processing System
PR	Precipitation Radar
PRF	Pulse Repetition Frequency
QC	Quality control
QPE	Quantitative Precipitation Estimate
RCA	Relative Calibration Adjustment
R-CLIPER	Rainfall CLImatology and PERsistence (model)
RF	Radio Frequency
ROSES	Research Opportunities in Space and Earth Sciences

RPF	Radar Precipitation Feature
RSL	Radar Software Library
SADA	Solar Array Drive Actuators
SCF	Science Computing Facility
SCSMEX	South China Seas Monsoon EXperiment
SDPF	Sensor Data Procession Facility
SIGMETs	Significant Meteorological Advisories
SN	Space Network
SOC	State of charge
SPCZ	South Pacific Convergence Zone
SSM/I	Special Sensor Microwave/Imager
SST	Sea-Surface Temperature
TC	Tropical Cyclone
TCSP	Tropical Cloud Systems and Processes
TDRSS	Tracking and Data Relay Satellite System
TES	Tropospheric Emission Spectrometer
TEXMEX	Tropical Experiment in Mexico
THORPEX	The Observing-System Research and Predictability Experiment
TIFF	Tagged Image File Format
TOMS	Total Ozone Mapping Spectrometer
TMI	TRMM Microwave Imager
TMPA	TRMM Multi-satellite Precipitation Analysis
TPOCC	Transportable Payload Operations Control Center
T/R	Transmitter/Receiver
TraP	Tropical Rainfall Potential
TRMM	Tropical Rainfall Measuring Mission
TSDIS	TRMM Science Data and Information System
UAH	University of Alabama, Huntsville
UARS	Upper Atmosphere Research Satellite
UF	Universal Format
UK	United Kingdom
UN	United Nations
USAID	U. S. Agency for International Development
USDA	U. S. Department of Agriculture
USGCRP	U. S. Global Change Research Program
USGS	U. S. Geological Survey
USRA	Universities Space Research Association
USSTRATCOM	U. S. Strategic Command
VHF	Very High Frequency
VIRS	Visible and Infrared Scanner
VR	Virtual recorders
WCRP	World Climate Research Program
WFF	Wallops Flight Facility
WMO	World Meteorological Organization
WSC	White Sands Complex
WSGT	White Sands Ground Terminal
WYE	Work Year Equivalent

Appendix D—References

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Appendix E — Technical Data

The lifetime analysis was performed in the light Dynamics Facility (FDF) using FreeFlyer. FreeFlyer is used in daily flight dynamics operations for the scheduling and planning of TRMM maneuvers. FreeFlyer contains an orbit propagator similar to that in the Goddard Trajectory Determination System (GTDS), and implements the Jacchia-Roberts 71 (JR) atmospheric density model. For TRMM lifetime analysis, long-term solar flux predictions produced by Dr. Kenneth Schatten, which are compatible with the JR density model, are used.

FreeFlyer determines propellant depletion by the mass flow method, using pressure-dependent thrust and Isp polynomials. A 92.7% Isp scaling factor has been adopted based on the results of a calibration run performed to match long-term propellant usage predicted by the mass-flow model to propellant remaining calculated by the pressure-volume-temperature (PVT) method. Starting from established initial and final PVT propellant remaining values, long-term propellant usage predictions were made using the mass-flow model. This process was repeated, adjusting the Isp each time, until the final mass-flow propellant remaining matched the final PVT value to within the uncertainty of the PVT value (7 kg). The PVT method is accepted as the most conservative and accurate method of determining the propellant remaining on TRMM.

Daily TRMM orbit determination solves for a drag correction value, called the “drag scale parameter,” a dimensionless parameter which represents the daily error in the predicted versus observed drag acceleration. In addition to errors in the atmospheric density model, this parameter also accommodates errors in spacecraft mass and area. For lifetime analysis, an average value of the drag scale parameter from July 18, 2003, to present is applied; this is the entire span that TRMM has been in its current configuration with the –Y solar array parked.

Table E1 summarizes the key modeling parameters employed in this analysis.

Table E1. Propagation Modeling Parameters

Start Date of Run	05 April 2010
Solar Flux and Geomagnetic Activity Model	Jacchia-Roberts 71, March 2010 Schatten Flux and Geomagnetic data
Initial Wet Spacecraft Mass	2734 kg
Initial Fuel Mass	103 kg
Initial Tank Pressure	139.4 psi
Drag Scale Parameter	-0.2614
Spacecraft Area Model	Box-and-wing, modeling 0-degree stowage of the –Y solar array
Thrust Polynomial	Nominal
Isp Polynomial	92.7% Nominal

Figure E1 displays predicted TRMM propellant usage generated using the March 2010 Schatten Mean Flux/Nominal Timing (MeanNom) and +2-sigma Flux/Early Timing (PlusEarly) solar predictions. These solar flux cases were chosen to provide realistic conservative and nominal bounds for the expected lifetime. The minus 2-sigma and late timing cases are expected to be too optimistic, and therefore are not included in this analysis. Also shown for reference is the propellant usage predicted had the TRMM orbit not been raised to an altitude of 402.5 km in August 2001.

Table E2 summarizes the new lifetime predictions. As of April 05, 2010, TRMM has 103 kg propellant remaining, which is less than the 138-kg propellant reserve required for a controlled re-entry from a 320 km altitude. TRMM reached the 138-kg remaining level following maneuver #478, in August 2005. Assuming a nearly constant propellant usage per maneuver, as has been the case historically, TRMM is currently expected to run out of fuel after maneuver #597 leaving TRMM approximately 88 remaining maneuvers as of the time of this report.

There is an approximately 28 kg difference between the PVT and mass-flow value and this difference is slowly growing over time. The difference is believed to be at least partly due to consistent differences in the temperature telemetry required in each method of calculation. Analysis performed by Scott Glubke of the Flight Dynamics Analysis Branch has established the PVT value as determined for TRMM to be accurate to within 7 kg and the PVT result is therefore considered to be the official and most accurate estimate of current propellant remaining.

Table E2. Predicted Dates to 0 kg Propellant Remaining

Propellant Remaining	Earliest Date	Nominal Date
0 kg Remaining	June 2013	November 2014

The March 2010 predictions decrease TRMM lifetime by 12 to 18 months when compared to the March 2009 predictions, and are more similar to the March 2008 predictions. This is attributable to the fact that the March 2010 predictions have a higher peak that occurs earlier for Solar Cycle #24 when compared to the March 2009 prediction.

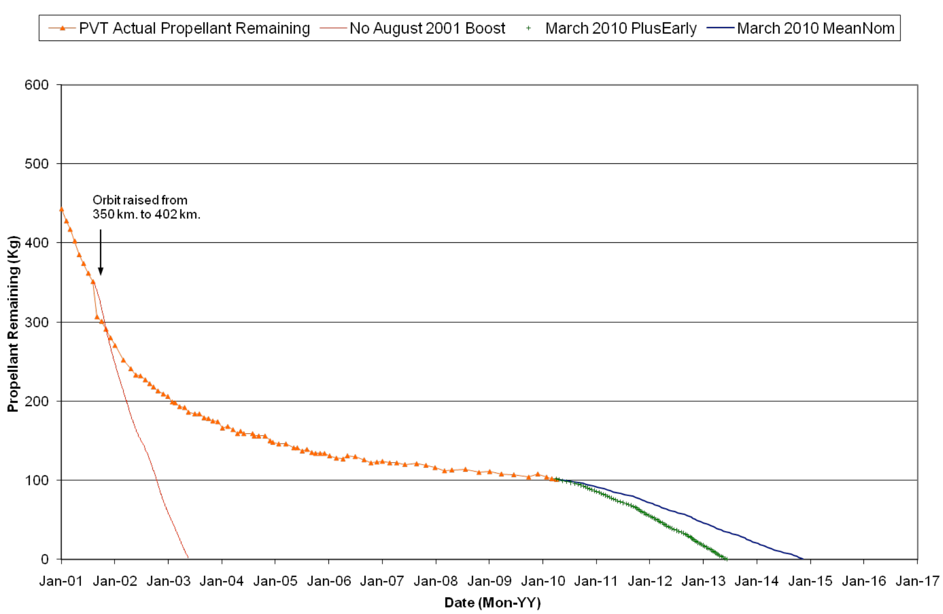

Figure 1. TRMM Lifetime – March 2010 Schatten Update