Open access • Journal Article • DOI:10.1007/BF01029783

On the Tropical Rainfall Measuring Mission (TRMM) — Source link

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Published on: 01 Mar 1996 - Meteorology and Atmospheric Physics (Springer-Verlag)

Topics: Climate model

The Tropical Rainfall Measuring Mission (TRMM) Progress Report

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Abstract

Recognizing the importance of rain in the tropics and the accompanying latent heat release, NASA for the U.S. and NASDA for Japan have partnered in the design, construction and flight of an Earth Probe satellite to measure tropical rainfall and calculate the associated heating. Primary mission goals are 1) the understanding of crucial links in climate variability by the hydrological cycle, 2) improvement in the large-scale models of weather and climate 3) Improvement in understanding cloud ensembles and their impacts on larger scale circulations. The linkage with the tropical oceans and landmasses are also emphasized.

The Tropical Rainfall Measuring Mission (TRMM) satellite was launched in November 1997 with fuel enough to obtain a four to five year data set of rainfall over the global tropics from 37°N to 37°S. This paper reports progress from launch date through the spring of 1999. The data system and its products and their access is described, as are the algorithms used to obtain the data. Some exciting early results from TRMM are described. Some important algorithm improvements are shown. These will be used in the first total data reprocessing, scheduled to be complete in early 2000. The reader is given information on how to access and use the data.

1. Introduction

The Tropical Rainfall Measuring Mission (TRMM) satellite has yielded important interim results after nearly two years of successful flight operations since launch in late 1997. This paper summarizes the mission science goals, instruments, algorithm development; some early results using the "at launch" algorithms, as well as ongoing efforts to validate the TRMM products. Section 2 contains the mission science goals, a brief summary of the joint project between Japan and the United States, and a table of the instruments. Section 3 describes the selected TRMM products, some of the algorithms developed to obtain the products, and the TRMM data system. Section 4 is a progress report on validation efforts. Section 5 presents some highlights of TRMM products during the first months after launch and their use in several research activities. Section 6 contains concluding remarks for this stage of the TRMM mission and a brief overview of the planned satellite system (Global Precipitation Mission) to succeed TRMM in measuring precipitation from space.

2. The goals, the TRMM Project, and the Instrument complement

The importance of tropical rainfall: TRMM goals

Tropical rainfall is important in the hydrological cycle and to the lives and welfare of humans. Three-fourths of the energy that drives the atmospheric wind circulation comes from the latent heat released by tropical precipitation. It varies greatly in space and time. Often severe droughts are succeeded by deadly floods. Many scales are involved in the rain processes and their impacts on global circulations. The rain-producing cloud systems may last several hours or days. Their dimensions range from 10 km to several hundred km, so that they cannot yet be treated explicitly in the large-scale weather and climate models. Until the end of 1997, precipitation in the global tropics was not known to within a factor of two. Regarding "global warming", the various large-scale models differ among themselves in the predicted magnitude of the warming and in the expected regional effects of these temperature and moisture changes. Accurate estimates of tropical precipitation and the associated latent heat release were urgently needed to improve these models. The agreed upon science goals of TRMM as presented in the first major report [1] are shown in Table 1.

Although tropical precipitation is organized on the mesoscale, it is noteworthy that primary objectives of the mission were to help improve climate models and aid them in climate prediction.

The TRMM Project

TRMM is a joint project between the United States and Japan, with the participation of many other nations in the science and validation. These include Australia, France, Germany, Israel and Thailand.

A Science Steering Group outlined the proposed science and instrumentation during a joint feasibility study in the United States and Japan. This was completed in 1988 [1]. Because of funding delays; the actual TRMM Project did not start until 1991. Japan supplied the crucial new instrument (rain radar) and the launch vehicle, while the United States supplied the other four instruments and the spacecraft. The Project kept a tight schedule within limited budget and TRMM was successfully launched in November 1997.

TABLE 1 - TRMM GOALS

I. TO ADVANCE THE EARTH SCIENCE SYSTEM OBJECTIVE OF UNDERSTANDING THE GLOBAL ENERGY AND WATER CYCLES BY PROVIDING DISTRIBUTIONS OF RAINFALL AND LATENT HEATING OVER THE GLOBAL TROPICS.
II. TO UNDERSTAND THE MECHANISMS THROUGH WHICH CHANGES IN TROPICAL RAINFALL INFLUENCE GLOBAL CIRCULATION, AND TO IMPROVE ABILITY TO MODEL THESE PROCESSES IN ORDER TO PREDICT GLOBAL CIRCULATIONS AND RAINFALL VARIABILITY AT MONTHLY AND LONGER TIME SCALES
III. TO PROVIDE RAIN AND LATENT HEATING DISTRIBUTIONS TO IMPROVE THE INITIALIZATION OF MODELS RANGING FROM 24 HOUR FORECASTS TO SHORT-RANGE CLIMATE VARIATIONS
IV. TO HELP UNDERSTAND, DIAGNOSE AND PREDICT THE ONSET AND DEVELOPMENT OF THE EL NIÑO, SOUTHERN OSCILLATION AND THE PROPAGATION OF THE 30-60 DAY OSCILLATION IN THE TROPICS
V. TO HELP UNDERSTAND THE EFFECT THAT RAINFALL HAS ON THE OCEAN THERMOHALINE CIRCULATIONS & THE STRUCTURE OF THE UPPER OCEAN
VI. TO ALLOW CROSS-CALIBRATION BETWEEN TRMM AND OTHER SENSORS WITH LIFE EXPECTANCIES BEYOND THAT OF TRMM ITSELF.
VII. TO EVALUATE THE DIURNAL VARIABILITY OF TROPICAL RAINFALL GLOBALLY
VIII. TO EVALUATE A SPACE-BASED SYSTEM FOR RAINFALL MEASUREMENT

The TRMM instruments

To meet the science goals, within limited resources, the final instruments are shown in Table 2. Their scanning patterns are illustrated in Figure 1.

Table 2

TRMM SENSOR SUMMARY - RAIN PACKAGE

MICROWAVE RADIOMETER (TMI)	RADAR (PR)	VISIBLE/INFRARED RADIOMETER (VIRS)
10.7, 19.35*, 21.3, 37,	13.8 GHz	0.63 μm VIS & 10.8 μm IR,
85.5 GHz (dual polarized)	4.3 km footprint	also 1.61, 3.75 & 12 μm
*21 km resolution	250 m range	@ 2.2 km resolution
at 19 GHz	resolution	
760 km swath	215 km swath	720 km swath

ADDITIONAL INSTRUMENTS: ONE CERES (CLOUD & EARTH RADIANT SYSTEM) & ONE LIS (LIGHTNING IMAGING SENSOR)

More complete information on all instruments and data is on or linked to the TRMM Web Site: http://trmm.gsfc.nasa.gov/
TRMM's radar (PR) is the first rain radar to operate from space. The passive microwave radiometer (TMI) is a multi-channel dual polarized, conically scanning passive microwave instrument similar to SSM/I. The Visible/Infrared radiometer (VIRS) is similar to the AVHRR. The purpose of the Visible/Infrared instrument was to enable TRMM to be a "flying rain gauge". TRMM's physically based results from the combined radar and passive microwave instruments are thus enabled to calibrate the surface rain estimations made empirically from operational geosynchronous IR sensors. Using this method with geosynchronous products obviated the restricted sampling by TRMM alone, which would overfly a given 5° by 5° grid box only about twice in 24 hr.

The radar and radiometer combination enables high quality precipitation profiles. The small cloud drops that play an integral part in the latent heat release process, however, would not be observable with sufficient accuracy to construct profiles of the latent heat release. It was therefore planned from the start to use results of a cloud-resolving numerical model in retrieving the important latent heat profiles.

Since rain is such a difficult variable to measure by any means, many debates were concerned with validation and confidence levels for the TRMM products. In addition to calibration plans, a plan for so-called " ground truth" using surface radars, gauges, and other networks is part of the mission. In view of the complexity of ensuring properly sited and quality-controlled surface radar data world wide, a special group was established to help formulate and implement a "Ground Truth" science plan.

The TMI is a passive microwave sensor designed to provide quantitative rainfall information over a wide swath. By carefully measuring the minute amounts of microwave energy emitted by the Earth and its atmosphere, TMI is able to quantify the water vapor, the cloud water and the rainfall intensity in the atmosphere. It is a relatively small instrument that consumes little power. This, combined with the wide swath, the extensive heritage in the Special Sensor Microwave/Imager (SSM/I), and the good quantitative information regarding rainfall makes the TMI the "workhorse" on the rain-measuring package of TRMM.

The precipitation radar PR (developed by CRL and NASDA in Japan), is a new instrument. It obtains unique rainfall information by its 215-km cross-track scan through nadir. The instrument is a 128-element active phased array system, operating at 13.8 GHz. The nadir footprint of PR is 4.3 km, with a vertical resolution of 250 m. The minimum radar reflectivity factor is about 18 dBZ, corresponding to a rain rate of about 0.5 $mmhr^{-1}$.

The VIRS is a five channel imaging spectroradiometer with bands in the wavelength range from 0.62, 1.61, 3.78, 10.8 and 12.0 μm. The VIRS provides cloud top temperatures. Its primary use to TRMM precipitation studies involves calibration of IR rain estimates as described in Section 5. It provides a link between the precipitation derived during the TRMM mission and similar IR estimates made in the past, from geosynchronous and low Earth orbiting sensors. VIRS is also essential to the climate and radiation studies the CERES Science Team is studying (see Section 5).

The VIRS is, in many ways, similar to the Advanced Very High Resolution Radiometer (AVHRR) that has flown since 1978 on the National Oceanic and Atmospheric Administration (NOAA) series of spacecraft in that both have the same center wavelengths and bandwidths. The major differences between the two systems is the 2.11 kilometer nadir IFOV of VIRS in contrast to 1.1 kilometer 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. The swath width resulting from the 350 kilometer orbit and a ±45 degree scan is 720 kilometers. All three of the rain instruments are described fully in a paper by Kummerow et al. [2].

The Lightning Imaging Sensor (LIS) [3], [4] consists of a staring imager which is optimized to locate and detect lightning (cloud-to-cloud, intra-cloud, and cloud to ground). Individual pixels within the 600 x 600 km total field-of-view correspond to an area 4 km by 4 km at the ground directly below the satellite, increasing in size to 7 km on a side at the edges of the field of view. TRMM travels a distance of 7 km every second, thus allowing the LIS to observe a point on Earth or a cloud for almost 90 seconds. Despite the brief duration of an observation, it is long enough to measure the flashing rate of most storms. The instrument records the time of occurrence, measures the radiant energy, and determines the location of each lightning event within its field of view. The sensor uses a wide field-of-view expanded optics lens with a narrow-band filter in connection with a high-speed charge –coupled device detection array. A real time event processor, inside the electronics unit, is used to determine when a lightning flash occurs, even in the presence of bright sunlit clouds. Some early results from LIS are shown in Section 5. Further information is obtainable via a link to the TRMM Web Site.

The Cloud and Earth's Radiant Energy Sensor (CERES) [5] is an improved version of the ERBE (Earth Radiation Budget Experiment [6] scanning broadband radiometer). The CERES instrument field of view is 10 km at nadir for the 350 km TRMM orbit altitude. The CERES scanners are capable of scanning in either a fixed azimuth (e.g., cross track for global coverage) or by rotating in azimuth angle as it also scans in elevation: thereby achieving the first hemispheric broadband measurements since the Nimbus 7 radiometer in 1978/79. CERES is designed to be flown with a cloud imager capable of accurate and stable estimates of cloud fraction, height, optical depth, emissivity, water phase and particle size. The imager is used along with the rotating azimuth plane CERES data to develop improved models of the shortwave and longwave anisotropy of clear and cloudy conditions. These new anisotropic models are then used to more accurately convert the radiance measurements into radiative fluxes. The imager cloud properties are also used to improve estimates of surface radiative fluxes as well as estimates of radiative fluxes within the atmosphere. The VIRS imaging instrument on TRMM fills this function [7]). The first products to be released are the ERBE-Like top of atmosphere fluxes. These data are processed with the ERBE algorithms, allowing comparison to the ERBE historical

data. Large amounts of information on radiation, including the validated CERES ERBE-like data are available at
http://eosweb.larc.nasa.gov/project/ceres/table_ceres.html

A more detailed pre-launch description of the science and engineering development of TRMM is given by Simpson et al. [8]. The rainfall instrument package is discussed fully by Kummerow et al. [2]

3. TRMM Rainfall Products, Algorithms, and Data System

Rainfall products, their error bars, and the vertical structure of latent heating form the cornerstone of TRMM science. In designing the data systems to generate these products under the very tight budget constraints, it was necessary to minimize the set of products that would satisfy the mission requirements. This section presents an overview of the products deemed critical to the mission success. A summary of these products is presented in Table 3.

Table 3: TRMM Satellite Products

Name	Ref. no.	Purpose
(a) Basic data		
VIRS radiances	1B-01	Calibrated, geolocated radiances
TMI brightness	1B-11	Calibrated, geolocated, Brightness Temperatures
PR Power	1B-21	PR power/ noise level
PR Reflectivities	1C-21	Basic reflectivity data; Missing if no rain.
(b) Geophysical parameters		
Surface cross-section	2A-21	Radar surface scattering cross-section/total path attenuation.
PR Rain type	2A-23	Type of rain (conv/strat) and height of bright band.
TMI profiles	2A12	Sfc. rainfall and 3-D structure of hydrometeors and heating over TMI swath.
PR profiles	2A-25	Sfc rainfall and 3-D structure of hydrometeors over PR swath
PR/TMI Combined	2B31	Sfc. rainfall and 3-D structure of hydrometeors derived from TMI and PR simultaneously
(c) Time/space avg. parameters		
TMI monthly rain	3A-11	Monthly 5° rainfall maps - ocean only.
PR monthly avg.	3A25	Monthly 5° rainfall and structure statistics from PR
PR Statistical	3A26	PR monthly rain accumulations - statistical method.
PR/TMI monthly avg.	3B31	Monthly accumulation of 2B31 products & ratio of this product with accumulation of 2A12 in overlap region.
TRMM and Others	3B42	Geostationary precip. data calibrated by TRMM. Rain at 5 day, 1° resolution
Merged Satellite	3B43	TRMM, calibrated IR and gauge products – data merged into single rain product. 5 day, 1° res.

Data levels

Level 1 data are calibrated and Earth located data from the primary TRMM instruments. Coding of the calibration and geolocation algorithms was performed by the TRMM Science Data and Information System (TSDIS) for the TMI and VIRS and by NASDA for the PR. The only additional product at level 1 is the PR reflectivity (ref. 1C-21). In this algorithm the radar returned power is converted into radar reflectivity factor, the quantity most often used in science applications. In addition to the conversion, a decision is made regarding the existence of rain in the radar FOV. If no rain is detected, the entire set of reflectivity factors along the column is set to a missing value. This was done to help reduce data volumes in compressed file formats.

There are five Level 2 products. In the NASA terminology, Level 2 products refer to geophysical parameters derived at the satellite footprint level. Level 2 and higher level algorithms were all written by the TRMM Science Team members from the U.S. and Japan and integrated into the TRMM Science Data and Information System (TSDIS) approximately one year before the TRMM launch.
Level 3 products are averages over specified space and time intervals; there are six.

TRMM products and their algorithms: Evolutionary Stages[1]

The "at launch" or Day 1 algorithms for all the products in Table 3 were in place in the data system considerably in advance of launch and their software had been tested. A basic TRMM philosophy is that the first two yeas in flight would be devoted to testing of the algorithms' performance, estimating the error bars of the products by several methods, beginning with the instrument calibrations. Better algorithms have been developed near the end of the second year. A reprocessing of the data with the improved Day 2 algorithms began in October 1999; the updated products will be made available to the science community approximately 8 months later. Two more cycles of algorithm improvement and reprocessing are planned by the end of the third flight year. The recalculations will benefit from the additional observations acquired as the flight mission continues. In this Progress Report, the results presented in Section 5 are derived from the Day 1 "at launch" algorithms. Validation and testing are discussed in order to show how much better the TRMM system is able to perform, so that greatly improved products should be available by about June 2000.
Here we will discuss only four unique particularly interesting algorithms in their Day 1 versions.

[1] A paper explaining the details of the algorithms, calibrations and improvements is in progress by Kummerow at al. at the Goddard Space Flight Center.

TMI Profiling Algorithm - (ref. no. 2A-12): The TMI profiling algorithm[2] 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 then 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 corresponding cloud model profiles to derive new composite profile. The basic technique is described in more detail in [9]. An example obtained from TMI during the Supertyphoon Paka study is shown later in Figure 5.

The output product from 2A-12 consists of the surface rainfall rate and a confidence parameter, as well as the 3-D structure 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. Since TRMM does not capture the small droplets where the latent heating is released, the chosen profile must also come from cumulus cloud model. In 2A-12, the heating profiles are imported from the cumulus cloud models along with the hydrometeors. The associated latent heating profiles will be made available once confidence in the rain profiles has been established.

Over land, where the emission signature cannot be detected directly, the precipitation will have a strong model dependence. To minimize the model dependence, a semi-empirical relation based on [10] is used. The formalism is the same as that used over land in order to keep the "at launch" algorithms simple.

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[2] This algorithm is referred to as GPROF, standing for Goddard Profiling algorithm; it is undergoing substantial improvements which will lead to excellent profiles of precipitation hydrometeors and latent heat release.

PR profile - (TSDIS ref. 2A-25)- Algorithm 2A-25 is a deterministic algorithm to retrieve rain parameters over each resolution cell by applying a profiling method using the path-integrated attenuation. The path-integrated attenuation is estimated by the weighted average between the SRT (2A-21) and the Hitschfeld-Bordan method where the weight is proportional to the relative accuracy of the methods. The 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 rainfall rate estimate is given at each resolution cell (4 km times 4-km time's 250 m) of the PR. This algorithm basically uses a hybrid method described in Iguchi and Meneghini [11] to estimate the true vertical radar reflectivity (Z) profile. The vertical rain profile is then calculated from the estimated true Z profile by using an appropriate Z-R relationship. One major difference from the method described in the above reference is that in order to deal with the beam-filling problem, a non-uniformity parameter is introduced and is used to correct the bias in the surface reference arising from the horizontal non-uniformity of rain field within the beam. The Z-R relationship is adjusted according to the rain type, the altitude, the correction factor in the surface reference method, and the non-uniformity parameter. Relatively minor calibration changes have been made [12, 13, 14], which are incorporated in the algorithm for the data reprocessing.

Combined PR/TMI Profiling Algorithm (TSDIS ref. 2B-31) The guiding principle in the design of the "at launch" combined algorithms was to merge information from the two sensors into a single retrieval that embodied the strengths of each sensor. After much debate, it was decided to use a very conservative approach in the beginning. The algorithm designed to run at launch uses the 10 GHz channel of the TMI to obtain an independent estimate of the total path attenuation at 13.8 GHz, the frequency of the TRMM Precipitation Radar (PR). This is possible because low frequency brightness temperatures are well correlated with total path attenuation.

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, where

$$Z = a(s',D')R^{b(s',D')} \text{ and } k = \alpha(s',D')R^{\beta(s',D')}.$$

In summary, the problem can be stated as follows. One has profiles of measured radar reflectivities represented by the vector Zn (the components of each vector are the reflectivities from the various range bins, and the index n refers to the n'th radar beam), along with Surface Reference Technique (SRT) estimates of the path-integrated attenuations in each of N radar beams constituting a radiometer beam (n = 1, ..., N), and associated measured 10.7 GHz brightness temperature T_b. This may be inverted to obtain a unique estimate of the rain rate profile R_n along with the shape parameters of the DSD, assuming the DSD shape parameters are uniform in altitude and within the radar beam [14].

Combined Instrument Monthly Rain Profiles - (TSDIS ref. 3B-31) -- This algorithm uses rainfall and vertical structure output from 2B-31 over the PR narrow swath and compares it to the rainfall-vertical structure results from TMI algorithm 2A-12 product on monthly time scales. This is accomplished by sub-sampling the 2A-12 product to the 2B-31-product scale, with calibration coefficients calculated at 5° grid elements based upon their comparison within the inner swath. For the at-launch algorithm, an individual calibration coefficient within a grid box is obtained by determining the scale factor that transforms the average of 2A-12 pixels to the average of 2B-31 pixels over the narrow swath intersection. The output consists of monthly accumulations from the wide swath 2A12 product, along with the ratio of the 2A-12 to 2B-31 over the coincident (narrower) swath of the radar.

The TRMM Science Data and Information System (TSDIS)

TSDIS generates the TRMM standard products and is responsible for distributing data to the TRMM algorithm development team. The broader distribution of data is performed by the Goddard DAAC (Distributed Active Archive Center). The interface to both data systems is Web based and both can be accessed from the TRMM Web site whose address was given above. For Japanese TRMM scientists and associated community, these same products are also available through the NASDA EOC data system accessible via: http://www.eorc.nasda.go.jp/TRMM/

Overall status of TRMM algorithms and data production in 1998- 1999

Because of the early success of the data system, TSDIS was able to support significant expanded capabilities. In July 1998, TSDIS began generating near real-time data products. The products are the same as the official products described above, but the output data has been reduced drastically to only those parameters that might be of use to the real-time users. This includes surface rainfall and 20 (instead of 80) layers of the PR vertical structure. Authorization is needed to obtain these products, but instructions on obtaining them may be found on the TSDIS Web page accessible from the main TRMM site at http://trmm.gsfc.nasa.gov.

The second product, on which testing began in June of 1999, is a 0.5 degree gridded data set generated specifically at the request of the TRMM Modeling Team. This data set contains the gridded average rainfall rate, and convective percentage along with the necessary record keeping variables needed to reconstruct the scenes. For ease of use, this product is given in text format. The TRMM data set consists of the TMI, PR and Combined TMI/PR products. Plans are being made to add SSM/I derived rainfall and convective fraction, and eventually the calibrated rainfall rates from geostationary IR observations in the same format. This will allow the user community easier access to surface rainfall rates from a multiplicity of sources that may be combined in any number of ways to achieve the users' needs.
The first minor reprocessing which included format changes for some products were made in September 1998. The first major reprocessing with improved algorithms began in October 1999.

4. Validation efforts during first two flight years

Validation begins with testing the calibration of the instruments, which is done just before launch and again in orbit.

TMI calibration

At the end of the active earth-viewing part of the scan, the TMI goes through a two-point calibration process, which consists of one measurement each at a " hot" and at a "cold" reference temperature which is repeated every scan period. The earth-viewing raw data from the active scan are converted to microwave brightness temperatures by using the two-point calibration measurements plus the antenna parameters such as the spillover and cross-polarization, etc. [2]. Numerous statistical comparisons between TMI and SSM/I's have been made over oceans as well as land. These comparisons show the TMI is approximately 10°K too warm at the 0°K end when the curves are extrapolated to the low calibration end. At 300°K, agreement between TMI and SSM/I is good. This bias is also consistent with a ~13°K temperature measured by TMI looking at the cosmic background radiation (Frank Wentz, personal communication).

The bias correction will be applied to the TMI data beginning with the October 1999 reprocessing.

PR calibration

In the initial checkout of the PR, which was conducted for 2 months after the TRMM launch, the PR system gain was determined by means of the Active Radar Calibrator (ARC). As a result, it was confirmed that the calculated PR receiver gain, based on the data obtained on the ground before the launch and using the telemetered temperatures on orbit is about 0.6 dB higher than the ARC calibration result, while the PR transmit power is about 0.6 dB lower. Those results were implemented as correction factors to calculate the PR received power and radar reflectivities. Since the completion of the initial check-out, the PR system characteristics, monitored by the telemetered data, the ARC calibration and the internal calibration, have shown excellent stabilities except for cases where unusual temperature changes occurred due to power shutdown for satellite maintenance. Both transmit and receive path gains calibrated by the ARC have shown variations within +/- 0.2 dB around the corrected receiver gain. Sea surface return levels measured at incidence angles between 6 and 10 degrees, known as the most insensitive to surface roughness, are quite consistent with previous measurements by Ku-band airborne radars developed by JPL and CRL, and are stable within about +/- 0.2 dB. Moreover, comparisons of PR-measured radar reflectivities of rainfall with those measured at NASA's Florida ground validation site [15] and by the MU radar of Kyoto University show excellent agreements with average differences of about 1 dB [16]. Those calibration and validation results indicate that the PR system characteristics are sufficiently stable and accurate to ensure reliable radar reflectivity and surface radar cross-section measurements. Improvements in the PR calibrations are used in the first data reprocessing which began in October 1999.

VIRS Calibration

The VIRS radiometric calibration algorithm converts the digital data downlinked from the instrument into spectral radiances. The calibration coefficients for the visible and shortwave infrared bands were determined in the laboratory before launch. VIRS carries a reference blackbody that is used to update the calibration coefficients for the thermal bands for each scan of the instrument on orbit. In addition, VIRS uses an onboard diffuser to view the sun approximately one per month. THE VIRS radiometric algorithm uses measurements of these reference sources to provide calibrated spectral radiances for each Earth pixel that it views.

On orbit characterization of response vs. scan angle (scan mirror reflectance) has shown differences of up to 2% from the pre-launch values in the thermal infrared bands located at 10.75 and 11.94 micrometers. Under low-light conditions, Channel 2 (1.6 microns) has some error, which is being corrected..

Comparisons of rain products from different algorithms

The next stage is to compare rainfall rates for the same areas and times by the different algorithms. An intensive set of comparisons of the "at launch" rain algorithms has been made by E. Smith. The algorithms for all products have been compared for numerous space and time intervals, from individual pixels up to 5° by 5° over a month. All these comparisons can be viewed on a link to the TRMM Web Site. [3] From these comparisons

[3] On the TRMM Web Site click on "TRMM related links" then " TRMM Research" and finally on TRMM rain algorithm intercomparisons at FSU.

and other information, Smith[4] developed an improved (versus "at launch") algorithm combining the PR and TMI. In this algorithm, the TMI is used to constrain the radar equation. Improvements were also made in the TMI vertical-profiling algorithm (GPROF).[5] About half the algorithm changes resulted from better instrument calibration, while the other half evolved from improved process and model reformulation.

Figure 2 shows the zonal ocean (above) and land (below) average rain rate for February 1998 as obtained by four improved algorithms over the ocean and three over land. These are the greatly improved algorithms that will be used in the October 1999 product recalculation by TSDIS. The agreement in Figure 2 is as good as expected at this stage of the mission, as was the somewhat lesser agreement among the "at launch" algorithms. In the important equatorial trough zone, the PR rainfall is much lower than the TMI products. Careful analysis showed that the difference was mainly the result of uncertainties regarding the size distributions of the hydrometeors. Hence, it is necessary to turn to other platforms, such as aircraft and ground radars, to determine whether the satellite products are credible, and also to improve the inadequate knowledge of particle size distributions.

The Ground Validation (GV) program, using surface and aircraft data

To increase level of confidence with which the TRMM products can be used, it is necessary to conduct special measurements at and near the Earth's surface. The TRMM Ground Validation (GV) program is composed of two primary efforts: climatological validation and physical validation. General objectives are to obtain an improved understanding of the physical processes associated with clouds and precipitation that ultimately lead to improvements in their remote sensing and representation in numerical models. In climatological validation, standard products are produced from various sites that have one or more calibrated radars and a network of regularly maintained rain gauges. The objective is to provide independent validation of the satellite products at select locations.

[4] Eric Smith, University of Alabama at Huntsville, personal communication.
[5] Ye Hong, personal communication.

Climatological Validation

Table 4 describes basic characteristics for the four primary validation sites. The primary sites are described in more detail on the TRMM Office web site at http://trmm.gsfc.nasa.gov/trmm_office/index.html. Radar and rain gauge data are provided on a continuous, routine basis to GSFC, from which standard products are generated. The exception is Darwin, in which data is received only during the 5-6 month wet season. The procedures used to generate these products are described in more detail at the Joint Center for Earth Systems Technology (JCET) GV web site at http://trmm.gsfc.nasa.gov/jcetop/jcet.html. This site also has extensive statistics, summaries of the meteorology and performance of the quality control algorithms for each pentad from each site, and rain map products. Products from five special climatology sites (Guam, Taiwan, Brazil, Israel, and Thailand) during select, 3-6 month periods of interest to TRMM are currently being generated by investigators from their home institutions.

Table 4 Description of the primary GV sites. All radars are Dopplerized. Also listed are the number of tipping bucket gauges that measure 1-min rain rates, which have been used in rain map production at GSFC.

Site	Radar characteristics	No. of gauges
Kwajalein Atoll, Republic of Marshall Islands (8.72 N, 167.73 E)	WSR-93D 10 cm polarized	9
Darwin, Australia (12.25 S, 131.04 E)	BMRC/NCAR C-POL 5 cm polarized	20
Melbourne, Florida (28.11 N, 80.65 W)	WSR-88D 10 cm	80
Houston, Texas (29.47 N, 95.08 W)	WSR-88D 10 cm	80

Data quality is a major challenge in climatological validation. The rainfall products are only as good as the quality of the radar and rain gauge data. Raw radar data is contaminated by returns from non-meteorological targets (bugs, birds, the surface [anomalous propagation], chaff, and wildfires). The current quality control algorithm requires an analyst to vary adjustable parameters in order to remove these echoes. Rain gauge data is also edited by comparing temporal and spatial correlations with radar-derived rainfall estimates (using $Z=300*R^{1.4}$) over the locations of the gauges. An automated procedure was developed that determines which of the gauges pass this quality control step [19, 20] and the algorithm performed very well when compared with manual inspection of the merged gauge-radar data. Hereafter those gauges that pass this quality control step will be referred to as "good" gauges. Monthly rainfall estimates improve by up to 50 percent when quality control measures are applied to the radar and gauge data sets [17, 18, 19].

Rain maps are generated from each of the primary sites following Steiner et al. [20]. Radar-derived rainfall estimates (using $Z=300*R^{1.4}$) over the locations of the good gauges are adjusted by 7-min averaged rain rates measured by these gauges. A final relationship is derived, $Z=A*R^{1.4}$, in which $A=300*(\mathbf{R}/\mathbf{G})^{1.4}$, **R** is the total rainfall estimated by the radar over the good gauges, and **G** is the accumulated rainfall measured by the good gauges. This bulk adjustment is applied separately for rainfall classifications, resulting in convective and stratiform ZR relationships, $A_{conv}*R^{1.4}$ and $A_{strat}*R^{1.4}$, respectively. This bulk adjustment is applied to a month of data from each site. If the total accumulation of rainfall from the sum of the good gauges is less than 250 mm, and then the procedure is applied to several months of data for that site, in order to avoid numerical instabilities in the procedure.

A comparison of TRMM products with the GV rain maps has been done in a preliminary fashion for Algorithm 3B-43. This is the one that uses TRMM results to adjust the Global Precipitation Index from geosynchronous satellites (see Section 5). The monthly rain estimates agree to within 20% for all of the sites with GV consistently estimating less rainfall. It is noteworthy that when the GV data were plotted on Figure 2, the points lay about midway between the TMI products and those of the PR.

Because surface radars require occasional maintenance and repair, they cannot operate continuously like satellites. A more definitive comparison is underway by taking a subset of the satellite measurements matched with the operating radars, in which the monthly GV and satellite rainfall estimates are expected to agree within 15%.

Field Experiments and Physical Validation

Table 5 lists the five different field experiments that were conducted during the first two years of the mission. These data sets will be used to evaluate the physical assumptions made by rainfall algorithms, initialize and validate the cloud resolving models, test latent heating retrievals from the TRMM observables, and evaluate methods of estimating rainfall and latent heating from ground based radars. In addition to this basic set of objectives, the field experiments were designed as a group in order to insure that the specific observations could also be compared between experiments in order to gain some insight into the regional dependence of any findings. A number of measurements are therefore common to all experiments.

Table 5. Summary of TRMM field campaigns. The presence of profilers (P), radiosondes (soundings, S), rain gauges (R), disdrometers (D), tethersonde and surface flux tower (T), and cloud-to-ground lightning detectors (L) in each experiment are listed in the last column.

Field Experiment	Location	No. of radars	No. of aircraft	Other platforms
TEFLUN-A (TExas-FLorida UNderflight Experiment)	Texas	3	2	P, S, R, L
TEFLUN-B (TExas-FLorida UNderflight Experiment)	Florida	2	2	P, S, R, D, T, L
SCSMEX (South China Sea Monsoon Experiment)	South China Sea	2	0	S, R, D
TRMM-LBA (TRMM-Large Scale Biosphere-Atmosphere Experiment in Amazonia)	Rondonia, Brazil	2	2	P, S, R, D, T, L
KWAJEX (KWAJalein EXperiment)	Kwajalein, RMI	2	3	P, S, R, D, T, L

The core of all experiments consisted of a pair of Doppler radars needed to obtain the vertical air motions that are critical to independently verify the latent heating profiles associated with precipitation. Similarly, all experiments had significant levels of meteorological soundings in order to initialize cloud scale models that provide the input for TRMM based latent heating estimates. Area-averaged divergence and budgets of heat and moisture will be derived from radiosonde networks in TRMM-LBA and KWAJEX. Comparisons among these various methods for arriving at the latent heating profiles must ultimately form the basis for any improvements in the latent heating profiles derived from the satellite.

The other objective of the Field Experiments is to validate the physical assumptions made by the TRMM retrieval algorithms. It is vital that the assumptions made by the

TRMM,sensor, as well as ground based algorithms be carefully checked in order to gain confidence that we not only have the right answer, but have it for the right reason. Foremost among these is verification that the TRMM radar is using statistically appropriate drop size distributions (DSD). To meet this goal, all experiments had at least one aircraft capable of measuring DSD in situ plus one aircraft capable of simulating the TRMM observations. The latter is important in order to insure that enough samples are obtained during each campaign. There were also excellent in situ measurements of ice, which documented the variations in habits and their particle size distributions as functions of temperature (height) in different parts of the storms. This important information should lead to improvements in the retrievals and in the cloud models.

5. Early Applications to science

Comparison of El Niño/La Nina

As discussed above, the TRMM data by themselves provide a uniquely accurate rainfall data set, but the sampling becomes inadequate for short intervals and small areas. However, it is possible to use the high-quality precipitation estimates from TRMM as the calibrating mechanism ("the flying rain gauge") for estimates from other satellite platforms and then combine them with rain gauge analyses. This scheme extends TRMM-like accuracy to space and time resolutions that are not available from TRMM alone.

Infrared (IR) data from geosynchronous satellites are useful in estimating rain because it detects the presence of clouds and because it has excellent time/space coverage. However, the physical connection between the IR radiances and the surface precipitation is relatively weak compared to TRMM sensors. For example, the GOES Precipitation Index GPI assigns a single rain rate to all pixels colder than a specified temperature threshold. Adler et al. [21, 10] showed that biases in the GPI could be minimized by adjusting the GPI rain rate in space and time to some other sparse, but accurate estimate. In TRMM this Adjusted GPI (AGPI) is produced by using cases of (nearly) coincident TRMM Combined Instrument (TCI; the combined TMI and PR algorithm) and VIRS IR data to compute a time- and space-varying IR - rain rate relationship that matches (i.e., is "adjusted" to) the TCI-inferred rain rate. The use of (nearly) coincident TCI and VIRS IR data prevents sampling issues from affecting the derived relations. The adjusted IR - rain rate relationships are then applied to the full geo-IR data to take advantage of the superior time sampling. To the extent that the TCI estimates are unbiased, the bias of the adjusted GPI ought to be small as well. The AGPI is produced operationally in TRMM as product 3B-42 by estimating the adjustment coefficients for calendar months on a 1°x1° lat./long. grid, then building estimates for five-day periods on the same grid.

The second step in producing an estimate from TRMM and other data is to integrate the AGPI with information from rain gauges. The satellite/gauge (SG) estimate is computed in two steps, following Huffman et al. [22]. First, the satellite estimate is adjusted to the large-area gauge information. For each grid box over land the AGPI estimate is multiplied by the ratio of the large-scale (5° x 5° grid-box) average gauge analysis to the large-scale average of the AGPI estimate. Alternatively, in low-precipitation areas the difference in the large-scale averages is added to the AGPI value when the averaged gauge exceeds the averaged AGPI. This procedure keeps the bias of the SG close to the (presumably small) bias of the gauge analysis on a regional scale, even while allowing the AGPI estimate to provide important local detail. Second, the gauge-adjusted AGPI estimate and the gauge analysis are combined with inverse-error-variance weighting. The errors employed in the combination are estimates of the (spatially varying) root-mean-square random error for each field, following [22]. The satellite/gauge estimate is now produced operationally in TRMM as product 3B-43 for calendar months on a 1°x1° lat./long. grid, which requires that the five-day AGPI estimates be (approximately) summed to the calendar months.

Figure 3 provides an example of the TRMM Satellite/Gauge estimates for selected months in 1998. It shows the expected climatological features, with maxima in the tropics in the Inter-Tropical Convergence Zone (ITCZ) in the Atlantic, Pacific and Indian Oceans; in the South Pacific Convergence Zone (SPCZ); and over tropical Africa and South America. Dry zones in the eastern parts of the subtropical oceans are evident. More pertinently, it depicts the peak of the 1997-98 El Niño at the start of the year and entry into the 1998-99 La Niña by the end of the year. Note the anomalous southward shift of the ITCZ and eastward shift of the SPCZ in February. Then there is a dramatic clearing of precipitation along the Equator as conditions return to normal. Finally, the whole tropical pacific pattern shifts westward as the La Niña sets in.

Tropical Cyclones: New views

Storms viewed in all ocean basins

TRMM marks the first time that tropical cyclones are examined from above by high-resolution down-looking rain radar. In the first 13 months of operation TRMM sampled 84 Tropical Cyclones with 1189 orbits passing within 750 km of a Tropical Cyclone center (19% of 6227 total orbits). This sample represents over an order of magnitude more data than can be obtained from any other platform. Statistical studies comparing storm characteristics, including rainfall in all oceans where these storms formed, are being carried out at NOAA's Hurricane Research Division.

Factors affecting intensity changes

The ability to forecast intensity changes in tropical cyclones has shown little progress in the past two decades. TRMM offers unique opportunities to identify both accelerators and brakes upon intensity. Within a few days after launch in November 1997, TRMM witnessed the birth of twin typhoons. An equatorial westerly wind burst flared up 2000-km southwest of Hawaii. PAKA formed in the Northern Hemisphere and PAM in the Southern. At first PAKA remained weak, until on December 10 a huge convective burst occurred (Figure 4). In the Figure, the upper left panel shows the geosynchronous view. The large round white area is the top of one of the early "hot towers". The upper right panel shows the TRMM radar superimposed on the geosynchronous image, while the lower left panel is the 85 GHz image from the TMI (TRMM Microwave Imager). Both the radar and the passive microwave show a clear eye, which was hidden on the geosynchronous image. The lower right shows a radar cross-section from A to B on the radar image above. The very high tower leans slightly inward toward the eye. Other radar cross sections show cloud material extruding from the cloud into the eye and almost surely sinking. The convective burst is associated with Paka's first rapid intensity increase from about 27 m s^{-1} to above 50 m s^{-1} on December 11. This first rapid deepening has been studied and related to a combination of the convective burst's carrying up high energy air [23] and the storm core moving over warmer [24].

Paka was a mature Typhoon until December 22, crossing the entire North Pacific. She caused great damage crossing Guam and became a Supertyphoon shortly thereafter. Rain and latent heat release profiles from TRMM are being studied in several stages of Paka's life. Figure 5 (a and b) shows an example late in her lifetime. The 2A-12 algorithm is used for the profiles. Cloud modeling is used for the latent heat release since TRMM does not sense the small cloud hydrometeors which actually release the heat as they condense from the vapor phase[6].

Improving assimilated global data sets using TMI rainfall and Total Precipitable Water (TPW) observations

The precipitation and total precipitable water (TPW) estimates derived from the TMI have proven to be effective for improving assimilated data sets. Conventional global analyses currently contain order-one errors in primary hydrological fields such as precipitation and evaporation, especially in the tropics. The TMI-derived rainfall and TPW estimates may be used to constrain these fields to produce a global analysis useful for understanding the role of tropical convection in global climate variability. Pilot studies carried out at the NASA Goddard Space Flight Center have shown that assimilating the 6-hr averaged TMI surface precipitation and TPW estimates improves not only the primary hydrological fields but also key climate parameters such as clouds and radiation in the analysis produced by the Goddard Earth Observing System (GEOS) data assimilation system (DAS). In this section we highlight some of the benefits of using TMI rainfall and TPW data in global data assimilation.

The precipitation and TPW assimilation algorithm used in the GEOS DAS is based on a 6-hr time integration of a column version of the GEOS DAS, which minimizes the least-square differences between the observed TPW and rain rates and those generated by the column model over a 6-hr analysis window. This "1+1" dimensional scheme, in its generalization to four dimensions, is related to the standard 4D variational assimilation

[6] All processes by which water substance changes phase are included in the model.

but employs moisture analysis increments instead of the initial condition as the control variable [25].

In assimilation experiments in which the 6-hr averaged GPROF rainfall [9] and Wentz's TPW retrievals [26] are assumed to be "perfect" relative to the model's first guess, the impact of these data on the GEOS analysis is to reduce the state-dependent systematic errors in tropical precipitation and TPW fields. Since clouds and radiation are directly affected by moist convection, the improved hydrological cycle, in turn, provides better estimates of atmospheric energetics. This is evident in the improved outgoing longwave radiation (OLR) and outgoing shortwave radiation (OSR) as verified against independent measurements provided by the Clouds and the Earth's Radiant Energy System (CERES) instruments aboard the TRMM satellite (CERES/TRMM 1998, see Section 5).

Figure 6 summarizes the impact of TMI rainfall and TPW assimilation on the monthly-mean precipitation, TPW, OLR, and OSR in the tropics for January 1998. These monthly plots are based on assimilation results sampled with the same spatial and temporal resolution as the satellite data sets used for verification. The left panel shows time-mean spatial errors in these fields in the GEOS control assimilation. The right panel shows the corresponding errors in an assimilation that incorporates the TMI rainfall and TPW observations. The monthly-mean spatial biases and error standard deviations are significantly reduced in most fields. The two apparent exceptions are the biases in the tropical-mean precipitation and OLR. The slightly larger precipitation bias reflects that the rainfall assimilation algorithm is more effective in reducing than enhancing precipitation, but the difference of 0.6-mm day^{-1} is within observation uncertainties. The apparent increase in the OLR bias is due to the virtual elimination of the negative OLR bias associated with precipitation, leaving tropical-mean bias dominated by the positive (but reduced) bias in the rain-free regions. In the GEOS analysis the OSR errors are dominated by errors in the clouds; the improved OSR is therefore indicative of improved cloud patterns.

Augmenting the TMI observations with rain rates and TPW estimates derived from two SSM/I instruments aboard the Defense Meteorological Satellite Program F13 and F14 satellites further enhances these improvements. For instance, with the addition of the SSM/I data, the error in standard deviation is reduced by about 20 per cent from those shown in the right panel.

In summary, this study shows that rainfall assimilation reduces the state-dependent systematic errors in clouds and the cloudy-sky radiation, while TPW assimilation reduces errors in the moisture field to improve the radiation in clear-sky regions. While the analysis also improves short-range forecasts in the tropics, these are relatively modest compared with improvements in the time-averaged "climate" fields. Overall, this work demonstrates the immense potential of using high-quality space-borne rainfall and TPW observations to improve the quality of assimilated global data for climate research and Numerical Weather Prediction applications.

Improving tropical precipitation forecasts from a multi-analysis super-ensemble

This study makes use of the notion of a multi-model super-ensemble developed by Krishnamurti et. al. [27, 28] for the improvement of seasonal climate, global weather, and hurricane track and intensity forecasts. In those two papers, we show that super-ensemble forecasts are invariably superior in skill to the individual multi-models. This same notion is being used here for demonstrating the large impact of TRMM data sets on global prediction of rainfall. Here, we first carry out what are called multi-analysis forecasts of rainfall. The multi-analysis comes from the use of different rain rate algorithms for the initialization (using physical initialization of rain rates, [29] for the several different rain rate algorithms). The initial rainfall distributions are estimated for the following options:

a) Control experiment that relies only on the model implied rainfall.

b) GPROF algorithm, Kummerow et. al. [9].

c) Olson algorithm, Olson et. al. [30].

d) Ferraro algorithm, [31].

e) TRMM 2A-12 algorithm [9].

f) Contribution from TRMM 2A-12 plus the Ferraro algorithm.

The basic procedure is to run 180 experiments with the FSU global spectral model at the resolution T126 (roughly 80km resolution) with these several options. Each experiment entails physical initialization of the observed rain (as measured by the different algorithms) and is followed by a three-day global forecast. After these experiments are completed, we prepare 'observed' fields of rainfall estimates (i.e. the benchmark) based on what we consider to be the best measures: Those are the TRMM 2A-12 applied to the TMI data sets and the Ferraro algorithm is also applied to all available SSM/I data sets from the three DMSP satellites, F11, F13 and F14. The entire data set generated from the multi-analysis based forecasts and the 'observed' best estimates are regressed to obtain weights via multiple regression for each of these forecasts weighed against the best 'observed' measures.

The next step in this exercise calls for a set of 30 new forecasts for a new period. Here the previously generated statistics (i.e. weights) are used along with the new multi-analysis forecasts to design superensemble forecasts three-days into the future. We show that it is possible to acquire very high forecast skills for rainfall from this superensemble that outperforms any of the direct forecasts from the use of the physical initialization of a single run with a single rain rate algorithm. What the results demonstrate is that much improved rainfall forecasts are now possible by the use of TRMM data sets. This success is related to the fact that we are able to make use of statistical relationships between model forecasts and observed estimates from TRMM. Using such statistics for the independent future forecasts, we can construct the much improved superensemble forecasts. The improvement is measured against our past performance, [32], when we used physical initialization and SSM/I based rain rates, estimated from Olson et. al. (1990) algorithm. Figure 7 illustrates a past skill, i.e. the correlation of predicted and observed rainfall, plotted against the forecast days. This illustration is based on Treadon [33]. Here we show that we have a very high nowcasting skill in these correlations, i.e. of the order of 0.9. This was a feature of physical initialization. The forecast skill degrades to 0.6 by day 1 of forecast. That skill degrades further by days 2 and 3 to values, such as 0.5 and 0.45 (respectively). Using the proposed superensemble approach, we are able to improve those numbers when the TRMM/SSM/I -based rain rates are used as a benchmark for the definition of the superensemble statistics and the forecast verification. Figure 8 illustrates the TRMM-based forecast skills over several selected regions of the globe. Here we note a major impact of TRMM towards improving regional short-range forecasts of precipitation beyond where we were in 1996.

Finally, in Figure 8 (a, b, c) we show correlation levels of about 0.7 between rainfall forecasts and the observed TRMM-based estimates. This is a major accomplishment from the use of TRMM satellite data.

Preliminary results on the diurnal variability of rainfall

Diurnal variation of precipitation is systematically investigated by using the Tropical Rainfall Measuring Mission (TRMM) precipitation products retrieved from TRMM microwave imager (TMI), precipitation radar (PR) and TMI/PR combined algorithms for year 1998.

Temporal variations of diurnal cycle of rainfall from 2A-12, 2A-25 and 2B-31 were averaged over ocean and land separately for the year 1998. The results over oceans are shown in Figure 9. It can be seen that the patterns of rainfall diurnal variability from different algorithms are similar. For an "at launch" algorithm, the agreement among the three is remarkably good. The dominant feature of rainfall diurnal cycle over ocean is a consistent rainfall peak in early morning, and a consistent rainfall peak in early-mid afternoon over land. The seasonal variation on intensity of rainfall diurnal cycle is clearly evidenced.

Horizontal distributions of rainfall diurnal variations indicate that there is clearly early-morning peak with a secondary peak in the middle-late afternoon in ocean rainfall at latitudes dominated by large-scale convergence and deep convection. There is also an analogous early-morning peak in land rainfall along with a stronger early-middle afternoon peak forced by surface heating. In addition, diurnal variations of seasonal rainfall over middle-Pacific and Indian Ocean are different. Over the Pacific Ocean, there are dominant early-morning and secondary late-afternoon rainfall peaks in spring and winter, with only an early morning rainfall peak in summer and fall. Over the Indian Ocean, however, there are strong late-morning and weak late-afternoon rainfall peaks in spring, only an early-morning peak in winter, while both early-morning and late-afternoon peaks occur in summer and fall. It is clear that tropical rainfall shows marked diurnal behavior, which is associated with large-scale convection. The diurnal variability has spatial and seasonal characteristics. More detailed discussion on rainfall diurnal variability is given by Yang [34].

The effects of improved rainfall measurements on understanding the upper ocean layers and the El Niño/Southern Oscillation[7]

Even as one of the strongest warm ENSO events was underway in the Pacific Ocean in 1997, the Indian Ocean experienced an anomalous event with an eastern equatorial cooling of over 3°C in the fall of 1997 and a warming of nearly 3°C during February 1998. The eastern equatorial Indian Ocean is akin to the western Pacific warm pool with a low SST variability and a semi-permanent barrier layer structure [35]. During fall 1997, alongshore wind anomalies along the coasts of Java and Sumatra led to complete elimination of the barrier layer and surface cooling due to coastal upwelling. The cold SST anomalies and the associated subsidence resulted in substantial reductions in precipitation in the east over Indonesia.

While ocean GCM simulations with climatological precipitation produce most of the cooling, interannual precipitation is required to match the observed SST anomalies closely [36]. This is because climatological precipitation provides higher precipitation in the east during fall 1997 and thus the barrier layer fails to vanish completely. However, interannual precipitation data from TRMM properly provides negative precipitation anomalies and thus leads to complete elimination of the barrier layer and surface cooling that is in excellent agreement with observations.

As the equatorial cooling in the east vanished by the end of 1997, the shift in the Walker circulation and associated convection towards Africa produced excess rain in the western equatorial Indian Ocean and over large parts of eastern Africa [37]. The western equatorial warming which further enhanced the East African floods was aided by precipitation and the accompanying freshening and shallowing of the oceanic mixed layer. These processes could not be simulated with climatological freshwater forcing for the ocean GCM. The increased rainfall of over 500% in some regions was accurately

[7] The work described in Section 5.7 was carried out by Dr. R. Murtugudde and colleagues of the Goddard Laboratory for Oceans/NASA.

captured by TRMM; this increased rainfall clearly improves the ocean GCM simulations of the event.

Model simulation of the warming in the eastern equatorial Pacific and the equatorial Atlantic are also improved noticeably by employing TRMM precipitation data. Without the interannual precipitation data from TRMM, the cooling to the east of 110W in the equatorial Pacific and to the east of 0E in the Atlantic is lower by over 1C. In a coupled model simulation, these SST differences will be even more significant since they will influence the equatorial SST gradient and have positive feedbacks through large-scale effects on the trade winds.

Early LIS results

With TRMM we can test hypothesis that ice formation and strong updrafts play the controlling role in most, if not all, cases of high cloud electrification. This relation, if valid, provides a unique method in inferring cloud updrafts coexisting with mixed ice and water. Figure 10 shows low to medium flash rate (1-3 flashes per minute) oceanic thunderstorms in the Atlantic Ocean basin (left panel) and a strong line of high flash rate (10-45 flashes per minute) storms over the Florida peninsula (right panel). The PR indicates these oceanic thunderstorms have peak reflectivity cores of 35 dBZ to a height of up to 8 km, whereas the deepest of the Florida storms show 35 dBZ reflectivity up to 12 km. Through examination of the TMI and PR profiles, we can determine the relationships among lightning rate, reflectivity structure, rainfall, and retrieved cloud properties. TRMM scientists have also been investigating the electrification of tropical cyclones and hurricanes. Throughout much of their life cycle these storms produce little or no lightning. When lightning is present, it is normally contained in the eye wall or rain bands. From initial TRMM observations, it has been determined that TMI ice scattering signatures are present in all cases when lightning was detected. While there is much research to be done on lightning in tropical cyclones, early indications are that the occasional, sudden bursts of eye wall lightning that occur in these storms is associated with a change in tropical cyclone intensity.

Very frequent intracloud lightning activity is observed when storms become severe. During the 3 May 1999 TRMM overpass of a tornadic supercell over east central Oklahoma, the LIS observed extreme total flash rates of 224 flashes per minute (only 7 cloud-to-ground discharges were observed by the U.S. National Lightning Detection Network). The PR indicated reflectivity in excess of 40 dBZ to an altitude of 14 km. At this same time the National Weather Service NEXRAD Doppler radar indicated a weak-echo region and a mesocyclone velocity couplet. The dominance of in-cloud lightning is an indication of the vigor of the storm updraft. Such relationships have been corroborated from ground-based VHF lightning measurements made at the central Florida validation site.

The 1997-98 ENSO and 1998-99 La Nina events produced interesting wintertime variations in lightning activity. Some of the most significant year-to-year changes occurred in the Gulf of Mexico and East China Sea (more thunderstorms during the ENSO winter), and in the South Pacific Convergence Zone (more thunderstorms during the La Niña winter [38]). In association with the strong upper level westerly jet anomaly over the Gulf of Mexico basin in the ENSO winter of 1997-98, there was a 150-200% increase in both lightning hours and lightning days year-to-year (between the winter of 1996-97 and the winter of 1997-98). An on-going examination of global thunderstorm activity variations during the ENSO and La Nina events is continuing.

Lastly, near-real time oceanic lightning data is provided by the LIS science team to the NOAA National Centers for Environmental Prediction/Aviation Weather Center (NCEP/AWC) for use in producing convective weather products needed by the aviation community for flight planning. The products use lightning data, geosynchronous satellite images (GOES, METEOSAT, GMS), and global model data to delineate hazardous areas aircraft should avoid. Further information on LIS and its data products may be found at http://thunder.msfc.nasa.gov.

Early CERES results

Two early CERES results have been of particular interest. First, the CERES rotating azimuth plane data were used by Hu et al. [39] to develop new anisotropic models for deep convective clouds with infrared window brightness temperatures less than 205K. Mean albedo for these clouds was 0.74, substantially less than the 0.80 maximum albedo expected from theory in the optically thick limit with a particle radius of 30 μm. To look for the thickest deep convective clouds, a subset of the deep convective data was analyzed for CERES fields of view classified as precipitating by the TRMM precipitation radar, as well as meeting the T<205K criteria. For these CERES fields of view, the average cloud albedo dropped to 0.70. As remarkable as this drop in albedo was the narrowness of the frequency distribution of the albedos for these precipitating deep convective clouds. The standard deviation of the CERES instantaneous field of view albedo was roughly 0.02, including the anisotropy errors in converting radiances to fluxes. One hypothesis for the different albedo for non-precipitating and precipitating deep convection is a change in ice particle size causing increased absorption by ice at near-infrared wavelengths. The VIRS imager on TRMM was matched to CERES fields of view, and the 1.6 µm near-infrared channel reflectance showed a substantial decrease in reflectance for the precipitating clouds, roughly consistent with the albedo drop of 0.04. Further analyses of these results are underway.

The second early CERES result of general interest is the surprising differences in tropical mean (20°S to 20°N latitude) Long-Wave fluxes between CERES in 1998 and the ERBE scanner climatology for 1985-1989 [40]. Figure 11 shows the tropical mean Long-Wave fluxes measured by the CERES scanner in January through August of 1998 compared to the ERBE scanner climatology for the same months in 1985-1989. The shaded area in the figure shows the total range (maximum to minimum) measured by the 5 years of ERBE data for each month, including the 1987 ENSO event. Two things are remarkable about this figure. First, the large change relative to ERBE between the peak of the 1998 ENSO event in February 1998 and the end of the El Niño phase in July/August of 1998. Second, even with the ENSO multi-variate index near zero [41] and other corrections, there remains 3.5 Wm^{-2} excess of the outgoing long wave radiation measured by CERES relative to ERBE. This potentially important result is undergoing further reality tests. For more updated CERES results, the reader is referred to CERES/TRMM, 1998: CERES Data Products Catalog. Available online from

http//:asd-www.larc.nasa.gov/ceres/trmm/ceres_trmm.html

Other exciting applications of TRMM data

There are several unforeseen ways in which TRMM data are being used to derive variables previously calculated only very approximately. An example is the retrieval of the latent heat fluxes from the ocean to the atmosphere to accuracy of ± 20-25 Wm^{-2} that will greatly improve energy budget calculations.[8] Most important, a thirty-day forecast experiment for the global tropics has been conducted using TRMM and SSM/I data in near real time (T. N. Krishnamurti, personal communication). The Superensemble methods described earlier are used. Great improvements in predicted rainfall have been found out to 3 days, with skill scores much better than those achieved by the commonly used general circulation models.

6. Conclusions and future work

It is clear from the validation tests and the applications of the actual rain and latent heating results discussed briefly in Section 5 that TRMM has met or will soon meet all of its goals presented in Table 1. A major impact of the mission will clearly be the long-run improvements of the global weather and climate models consequent upon assimilation of good quality latent heating in the tropics. Also there are some valuable results not expected during the pre-launch planning stage. The two most prominent of rain-related results are the data set on tropical cyclones and the usefulness of the lightning results from LIS in indicating the strong updraft regions in many types of cloud systems. The most important conclusion so far is that better-than-expected TRMM products came using the "at launch" algorithms, and substantial improvements in those have been large during the first 18 months of flight. Also, many other uses of TRMM data have been made.

Concerning whether much better agreement can be made between the PR, the TMI and the GV on the products depends upon the complex variations of the hydrometeor size distributions and how sensitive the different satellite products are to their local changes.

In this paper, we have tried so summarize the latest work in calibrating TRMM, achieving consistency among TRMM rainfall estimates with each other and ground based measurements and shown the tremendous impact that good satellite data can have both for the understanding of atmospheric phenomena, as well as improving data assimilation models an rainfall forecast efforts. There are many other research efforts within TRMM including the modeling of ocean surface temperature anomalies due to fresh water fluxes, land hydrology applications, and the rate of atmospheric overturning during the El Niño

[8] Work in progress. Personal communication from Dr. P. Bauer at DLR, Germany

of 1997-98 to name only a few. The latter in particular may begin to shed some light as to potential impacts to regional rainfall in a global warming scenario.

TRMM, however, cannot solve all the problems associated with precipitation. TRMM does not provide measurements outside of the tropics (35°N - 35°S), and its lifetime is only expected to be 3 years due to its low orbit. TRMM's greatest weakness, known from the early planning stage, is infrequent sampling. TRMM's sampling frequency at any given point by the TRMM radiometer is limited to approximately 1 sample every 15 hrs while the TRMM radar is limited to approximately 1 sample every 50 hrs (depending somewhat upon the latitude of the sample). The uncertainty due to insufficient temporal sampling can be studied using TRMM and ground-based validation data, but it cannot be overcome with a single, polar orbiting satellite. TRMM rainfall uncertainties are dominated by the sampling errors, and while TRMM's attributes are many, its short lifetime and crude sampling make it impossible to detect the subtle changes that may be associated with a slowly changing climate. TRMM was never designed to address those challenges. To address them, NASA and NASDA are beginning the planning phases of a new mission, the Global Precipitation Mission, tentatively planned for a 2006 launch.

The concept that has been formulated has two components. The primary satellite will be a single, enhanced, TRMM-like satellite that can quantify the 3D spatial distributions of precipitation and its associated latent heat release. It will consist of a dual frequency radar plus a multi-channel passive microwave radiometer. Using two frequencies, it will be possible to determine the first moment of the drop size distribution and thus rainfall rates that may exceed the quality of most ground based radars. The radiometer, as it does in TRMM, will help to gain further insight into the cloud properties as well as to relate these insights into the wider swath and the complementary satellites that form the second component of the concept.

The second component of the mission consists of a number of small radiometer satellites, which will provide the necessary sampling to reduce errors in time-averaged rainfall estimates to levels significantly smaller than the intrinsic errors in hydrologic and atmospheric models. With a total of 8 constellation radiometers (which may consist of any number of operational satellites such as the SSM/Is) the sampling frequency of 3 hours can be obtained. This will reduce the sampling errors to approximately 10% for daily rainfall accumulations. As demonstrated with early work related to TRMM, such data sets can have a tremendous both on data assimilation, model forecasting and hydrological applications. A new lightweight radiometer is currently being demonstrated by NASA to meet the needs of the Global Precipitation Mission.

The need for the continuation and extension to high latitudes of precipitation measurements is apparent.

Acknowledgments

The TRMM research reported herein was supported by Dr. Ramesh Kakar, Head of the TRMM Program at NASA Headquarters. The TRMM community greatly appreciates his support. So many fine scientists and engineers contributed to the success of TRMM that it is impossible to acknowledge them each by name. We wish particularly to thank A. Chang, K. Okamoto, T. Iguchi, H. Pierce, E. Stocker, R. Murtugudde, W. Barnes, J. Shuie, Y. Hong, W. Olson, E. Smith, and T. Wilheit, for making highly valuable contributions to this paper. We appreciate the contributions of many other members of the TRMM Science Teams in both the U.S. and Japan. Many members of the TRMM Project went far beyond the call of duty in making the mission a success, namely T. LaVigna, Project Manager, T. Williams, Deputy Project Manager, Tom Keating, Study Manager and Lead Engineer for the Project and many others who received a NASA Group Award for their efforts. Last but not in anyway least, we wish to express our great gratitude to Drs. N. Fugono and J. Theon for their invaluable help in starting the Project and seeing to its welfare and aid during its progress. We are very grateful to Otto Thiele for the management of the Ground Validation phase of the project and for doing a superb job heading the TRMM Office.

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Figure Captions

FIGURE 1. Schematic view of the TRMM spacecraft and the scanning patterns of the three rain instruments.

FIGURE 2. Comparison of TRMM monthly rainfall products for February 1998, ocean top, land bottom. Precipitation rate is plotted as a function of latitude. How each product is obtained is noted in Table 3. The black line is made from 2A-12, the green line 3A-11, the blue line 2A-25, and the red line 2B-31. The spatial resolution is 5° by 5°. These curves were calculated using the improved algorithms for the 1999 data reprocessing.

FIGURE 3. Selected months in 1998 of Satellite/Gauge estimates of global rainfall. The rain pattern is in transition from an El Niño to a La Niña pattern. "At Launch" algorithms used.

FIGURE 4. Geosynchronous and TRMM imagery of early stage of Supertyphoon Paka in the North Pacific at 0532 UTC on Dec 10, 1997. The upper left is GMS Geosynchronous image alone. Note bright convective burst near storm center. The upper right superimposes the TRMM radar image on the geosynchronous image. The lower left shows the TMI image superposed on the GMS and the lower right is a precipitation radar profile between A and B.

FIGURE 5. Rain and latent heat release ($Q_1 - Q_r$) profiles for Supertyphoon Paka when it is just past its peak intensity. The winds are estimated as 130 knots (~65 ms^{-1}). The quantities are averages over the inner 50-km ring, beginning at the outer edge of the eye. The first picture shows precipitation size hydrometeors in g m^{-3}. The second figure shows the net heat released by all the phase changes of water substance. Note the upper peak which suggests a warming contribution by the anvils, a fairly common feature of typhoons and hurricanes viewed by TRMM. These figures were made with the improved GPROF algorithm which is being used to reprocess all data beginning in October 1999. Courtesy of W. Olson.

FIGURE 6. NASA GEOS assimilation results with and without TMI observations for January 1998. The panels on the left show errors (compared to "observations" from TMI and SSM/I) in the monthly-mean tropical precipitation, total precipitable water, outgoing longwave radiation, and outgoing shortwave radiation in the GEOS control assimilation. The panels on the right show the impact of assimilating TMI rainfall and Total Precipitable Water (TPW) observations on these fields. The percentage changes relative to errors in the GEOS control are given in parentheses. See improved correlation AC between calculated and observed rainfall on the right side versus the left.

FIGURE 7. Skill of the precipitation forecasts over global Tropics, (30°S to 30°N). Abscissa shows dates of forecast. For control forecast, physical initialization uses TRMM data only. Superensemble forecasts use TRMM plus SSM/I rain rates as a benchmark.

a. Global tropics
b. Tropical Africa
c. Tropical Americas

FIGURE. 8. Comparison (in units mm day^{-1}) of observed rainfall (based on TRMM and SSM/I) with the day 3 forecasts from the superensemble approach: Forecast valid for August 5, 1998 12 UTC, for tropical Africa

FIGURE 9. Average diurnal variability in rainfall (mm day^{-1}) over all the oceans viewed by TRMM by month for 1998. The results from three different "at launch" algorithms are shown, namely top to bottom:

a. Combined TMI and radar
b. Radar profiling algorithm
c. TMI profiling algorithm

FIGURE 10. Lightning activity as sensed by the LIS instrument on TRMM. Left: Atlantic Ocean Basin. Right: A squall line moving down the Florida Peninsula.

FIGURE 11. Time Series of CERES/TRMM and ERBE/ERBS Scanner showing All Sky Top of Atmosphere Long-Wave Flux averaged 20°N to 20°S.

List of Acronyms

ADEOS II	ADvanced Earth Observation Satellite -II
AGPI	Adjusted Geosynchronous Precipitation Index
AMSR	Advanced Microwave Sounding Radiometer
API	Adjusted Precipitation Index
ARC	Active Radar Calibrator
ATI	Area Time Integral
AVHRR	Advanced Very High Resolution Radiometer
CERES	Cloud & Earth Radiant Energy Sensor
CRL	Communications Research Laboratory (in Japan)
DAAC	Distributed Active Archive Center
DAS	Data Assimilation System
dBZ	deciBels of Z
DMSP	Defense Meteorological Satellite Program
DSD	Drop size distribution
ENSO	El Niño/Southern Oscillation
EOC	Earth Observation Center
EOS-PM	Earth Observing System- Afternoon Platform
ERBE	Earth's Radiation Budget Experiment
ERBS	Earth's Radiation Budget Sensor
GCM	General Circulation Model

GEOS	Goddard Earth Observing System
GHz	GigaHertz
GMS	Geosynchronous Meteorological Satellite
GOES	Geosynchronous Operational Environmental Satellite
GPCP	Global Precipitation Climatology Program
GPI	Geosynchronous Precipitation Index
GPM	Global Precipitation Mission
GPROF	Goddard PROFiling Algorithm
Hz	Hertz
IFOV	Instantaneous Filed of View
IR	Infra Red
ITCZ	Inter Tropical Convergence Zone
JCET	Joint Center for Environmental Technology
KWAJEX	Kwajalein Experiment (for TRMM and model)
LBA	Large-scale Biosphere Atmosphere Experiment in Amazonia
LIS	Lightning Imaging Sensor
METEOSAT	Meteorological Satellite
Mbyte	megabyte
MHz	Megahertz
MU	Middle and Upper Atmosphere
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (of Japan)
NCEP	National Center for Environmental Prediction
NEXRAD	Next generation Radar

NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar Orbit Environment Satellite System
OGCM	Ocean General Circulation Model
OLR	Outgoing Long-Wave Radiation
OSR	Outgoing Short Wave Radiation
PIA	Path Integrated Attenuation
PR	Precipitation Radar
RPM	Revolutions Per Minute
SCSMEX	South China Sea Monsoon Experiment
SGM	Satellite Gauge Model
SPCZ	South Pacific Convergence Zone
SRT	Surface Reference Technique
SSAI	Science Systems and Applications, Inc.
SSM/I	Special Sensor Microwave/Imager
T_b	Brightness Temperature
TEFLUN A	Texas Florida Underflights - B
TEFLUN B	Texas Florida Underflights - B
TMI	TRMM Microwave Instrument
TOPEX	Topography Experiment
TPW	Total perceptible water
TRMM	Tropical Rainfall Measuring Mission

TSDIS	TRMM Science and Data Information System
VIRS	Visible and Infra-Red Sensor
Z	Radar reflectivity units $mm^6 m^{-3}$