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, 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 furnishes a brief overview of the planned satellite system (Global Precipitation Mission) to succeed TRMM in measuring precipitation from space. Section 7 contains concluding remarks for this stage of the mission's lifetime.

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

2.1 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 differed 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 (Simpson, Ed., 1988) are shown in Table 2.1

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.

2.2 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 (Simpson, Ed., 1988, loc cit.). 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 2. 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

2.2 The TRMM instruments

To meet the science goals, within limited resources, the final instruments are shown in Table 2.2.1. Their scanning patterns are illustrated in Figure 2.2.1.

Table 2.2.1

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 would thus be able 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 swathe, 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 swathe-crossing 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 noise equivalent reflectivity is about 20 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 5.1. 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 5.9).

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., 1998.

The Lightning Imaging Sensor (LIS) consist of a staring imager which is optimized to locate and detect lightning (cloud-to-cloud, intra-cloud, and cloud to ground) with storm-scale resolution (4 to 7 km) over a large region (600 by 600 km). TRMM travels 7 km every second, nearly 16,000 miles per hour, thus allowing the LIS to observe a point on Earth or a cloud for almost 90 seconds. The instrument records location, flash rate, the time of occurrence, and the radiant energy. 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 optics 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 5.8. Further information is obtainable via a link to the TRMM Web Site.

The Cloud and Earth's Radiant Energy Sensor (CERES) (Lee et al., 1998) is an improved version of the ERBE (Earth Radiation Budget Experiment; Barkstrom, 1984) 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 (Wielicki et al., 1996). 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. (1995). The rainfall instrument package is discussed fully by Kummerow et al (1998).

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 algorithms deemed critical to the mission success. A summary of these products is presented in Table 3.1 for reference.

Table 3.1: 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.

3.1 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. # 1C21). In this algorithm the radar returned power is converted into reflectivity, the factors 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 reflectivity 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.

3.2 TRMM products and their algorithms

TMI Profiling Algorithm - (ref. no. 2A-12): The TMI profiling algorithm 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 Kummerow et al. (1996). An example obtained from TM, I during the Supertyphoon PAKA study is shown later in Figure 5.3.2.2.

It should be emphasized that the result of the TMI profiling algorithm is the precipitation profile and approximately the $Q_1 - Q_r$ profile, where a small eddy flux has been omitted.

Q_1 is the total diabatic heating (or cooling) and Q_r is the radiative heating or cooling. Thus the so-called "latent heating" product of algorithm 2A12 is the heating or cooling produced by all phases changes of H_2O

The output product from 2A12 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). The associated latent heating will be provided once confidence in the rain profiles has been established.

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 2A12, the heating profiles are imported from the cumulus cloud models along with the hydrometeors.

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 the work of Adler et al (1994) is used. The formalism is the same as that used over land in order to keep the "at launch" algorithms simple.

TMI Monthly Rain Mapping Algorithm - (TSDIS ref. 3A-11)

The algorithm 3A11 generates Level-3 product of monthly totals of oceanic rainfall over 5° latitude by 5° longitude boxes using the TMI brightness temperature data as input. The algorithm is based on the Wilheit et al. (1991) technique. Chang et al. (1999) compared results of the technique between TMI and SSM/I data for six months of 1998 with encouraging results. There are three key features to this technique. First, the rain rate probability density function is constrained to follow a mixed-lognormal distribution. Second, a combination channel, twice the vertically polarized 19.35 GHz minus the 21.3 GHz, is used to reduce the effect of water vapor variability. Third, a rain-layer thickness (or freezing level) parameter, which is a proxy index of the total water in the rain column, is introduced. It is determined using information from the 19.35 and 21.3 GHz T_b histogram. For the purpose of this algorithm, the T_b are considered functions of only two variables, the rain rate and the rain layer thickness (freezing level). The monthly mean rain layer thickness determines a rain rate- brightness temperature (R-T_b) relation. Monthly mean rain rates are then calculated from parameters of the mixed-lognormal distribution.

TMI T_b data are first passed through a land mask filter to eliminate pixels that may be contaminated by land. Over 2000 lines of code have been manually added to the land mask database. The oceanic T_b data are then accumulated to generate the monthly brightness temperature histograms. The rain layer thickness (freezing level) is determined from the mean TB at the 21.3 and 19.35 GHz computed from the upper 99 percentile of the respective T_b histograms. The parameters of the mixed-lognormal rain rate distribution are calculated by matching the observed histogram of brightness temperature of the combination channel to a mixed lognormal rain rate distribution via the R- T_b relation. The monthly mean rain accumulation (mm/month) is calculated by multiplying the fractional rain by the conditional rain rate.

Surface Cross Section (TSDIS ref. 2A-21)

The primary objective is to compute an estimate of path attenuation and its reliability by using the surface reference technique (SRT). When rain is absent along the radar beam, the algorithm updates the statistics of the normalized radar surface cross section, σ^0. The data, accumulated on a monthly basis, are stored as a function of incidence angle over a 1° x 1° latitude-longitude grid. When rain is detected by the PR, the path-integrated attenuation or PIA is estimated by the difference between the apparent σ^0 in rain and the average value measured in rain-free regions. An associated reliability factor is also computed, based on the magnitude of the PIA relative to the variability of the rain-free σ^0 reference value. Secondary goals of the algorithm are to develop methods; similar to those developed for the TOPEX altimeter, for the estimation of surface wind speed and to use the spatial and temporal statistics of the surface cross sections for checking the instrument calibration.

PR Qualitative - (TSDIS ref. 2A-23) - Algorithm 2A-23 tests for the presence of a bright band and, if detected, determines its height. This information is also used to classify the rain type. Rain is classified into three types, i.e. (a) stratiform, (b) convective, and (c) others. The classification of convective/stratiform rain uses both a vertical as well as a horizontal structure of the precipitation. When the bright band exists, rain is, in most cases, classified as stratus. The horizontal texture of the precipitation is also examined. If a peak is present in the horizontal echo structure, and the peak is greater than a predetermined value, the precipitation is classified as convective. Cases where the above criteria are in conflict are assigned convective or stratiform types by the more reliable of the signals. When the bright band does not exist and all values of the reflectivity Z along the range are less than the predetermined value, rain is classified as "other". In the case of convective and "other" rain types, detection of "warm" rain is also carried out. When the storm height appears lower than the height of freezing level, the rain is judged as "warm" rain. The storm height itself is determined by a Level-1 algorithm by using the first range echo flag from 1C-21.

Detection of bright band is carried out by searching a peak of Z-factor with respect to range. This peak search is made by using a spatial filter, which is based on a second derivative of the range profile of the radar reflectivity factor. When the peak is prominent and appears around the expected height of freezing level, a bright band is judged to be present. When the bright band exists, the height where the peak occurs is regarded as the height of bright band.

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 (1994) 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.

Space-time Accumulations of Level 2 Radar Products - (TSDIS ref. 3A-25) - The primary objective is to compute the statistics over a space-time region for the output products of level 2 radar algorithms. In most cases the method of computation is a simple sample mean of the measurements made over the appropriate space-time domain. The most important output products are the monthly rainfall accumulations and monthly average rain rates over 5° x 5°. Boxes near the surface and at fixed heights of 2 and 4 km. Other products include histograms of radar and meteorological parameters, probabilities of rain and bright-band, and correlations among the various radar and meteorological parameters. The output data volume per month is of the order of 40 Mbyte.

Space-time Accumulations using Statistical Methods - (TSDIS ref. 3A-26) The objective is to compute rainfall accumulations and rain rate averages over 5° x 5° x 1 month boxes using a statistical method. The technique employed is a multiple threshold method. Measured rain rates over an area (intersection of the radar swath and a 5° x 5° region) that are within the 'effective dynamic range' are used to construct a partial histogram of the instantaneous area-wide rain rate. To estimate the distribution at all rain rates, a lognormal distribution model is assumed, the unknown parameters of which are determined by the measured data. As part of the method, the fractional areas over which the rain rate exceeds certain threshold values are computed and stored. These data provide a means of testing the area-time integral (ATI) methods that have been proposed (e.g. Short et al., 1993) The histograms of the instantaneous area rain rates are output for each overpass of each 5° x 5° box; they are also used to estimate the rainfall accumulations and rain rate averages over monthly periods.

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 in the first place.

A parameterization of the drop size distribution (DSD) using three mutually independent parameters is used. These are a) a quantity parameter R (the rainrate), and the two shape parameters D' and s', the first representing essentially the mass-weighted mean drop diameter and the second representing essentially 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 SRT estimates of the path-integrated attenuations An in each of N radar beams constituting a radiometer beam (so n = 1, ..., N), and an associated measured 10.7 GHz brightness temperature T_b^m. 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 (Haddad et al., 1997).

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 2A12 to 2B31 over the coincident (narrower) swath of the radar.

GPI Calibration Product - (TSDIS ref. 3B-42) Bob Adler to review - The TSDIS algorithm and code for Product 3B-42 is based on the Adjusted GPI (AGPI) technique described by Adler et al. (1994). The technique uses the output from 2B31 described earlier to objectively adjust rain rates inferred from geo-IR satellite observations and produce monthly total rain maps for the region 40°N to 40°S. The adjustment is based on the spatially variable ratio of rainrate estimates from coincident 2B31 and infrared data (VIRS) which is then applied to the full geo-IR data set. In its current version the algorithm produces a monthly product on a 1° lat./long grid. The temporal and spatial resolutions are dependent on the resolutions available in the GPI data sets supplied to the Global Precipitation Climatology Project (GPCP) by the geosynchronous-satellite operators.

Merge Satellite and Gauge Product - (TSDIS ref. 3B-43). The current algorithm for 3B-43 builds on the Satellite-Gauge-Model (SGM) technique described by Huffman et al. (1995), which makes use of the results in 3B-42. In the first stage, the Multi-Satellite intermediate precipitation product is produced from the TRMM Combined Instrument precipitation estimate (2B-31), the Adjusted GOES Precipitation Index (AGPI) precipitation estimate (3B-42), and an SSMI estimate that follows the 2A12 procedure. Estimates of the (spatially fluctuating) errors in each field are computed, mostly reflecting the sampling-induced uncertainty in each, then a linear combination is computed in which each estimate is weighted by the inverse of its (local) error-variance. This stage also yields the Multi-Satellite relative error estimate intermediate product. In the second stage, the Raingauge Precipitation Analysis (3A-45) and the Multi-Satellite precipitation estimate are similarly combined (using the 3A-45 rain gauge relative error analysis and the Multi-Satellite relative error estimate) into 3B-43 Satellite/Gauge precipitation estimate and relative error estimate fields. The primary limitation in the method is imperfections in the estimation of relative error for the individual fields.

3.3 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/

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

Because of the early success for 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 these may be found on the TSDIS Web page accessible from the main TRMM site at http://trmm.gsfc.nasa.gov.

The second product, which began testing 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. The ease of use this product is produced in text format. The TRMM product consists of the TMI, PR and Combined TMI/PR products. Since the TRMM product is working, it is planned to add SSM/I derived rainfall and convective fraction in an identical format, and eventually the calibrated rainfall rates from geostationary IR observations - also 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 pre-launch plans for TRMM emphasized that validation, algorithm improvement and complete recalculations of all products would occur regularly during the flight mission. The first reprocessing which included format changes for some products began in September 1998.

All research results on rainfall in Section 5 use the "at launch" algorithms. Where noted, some of the validation results use the next stage-improved algorithms. The entire data set will be reprocessed with the better algorithms beginning in October 1999. These results will be made available to all users approximately eight months later.

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.

4.1 Instrument Calibrations and tests thereof

4.1.1 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. (see Kummerow et al., 1998). 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. The source of this bias is still under investigation

4.1.2 PR calibration

4.1.2.1 Calibration strategy

The PR is the first rain radar to be operated for space, therefore it has no direct heritage. For this reason, it needs and has very careful in-flight calibration.

Accurate calibration of the PR is important to establish the clear interface condition between Level-1 and higher level algorithms, thereby assuring accurate and stable rain products. To develop the PR calibration algorithm, variation and drift of the PR system parameters are modeled to have "intermediate-term", and "long-term" components. The former is caused by the temperature change inside the PR and roughly has a period of one revolution (≈ 91 min). Thus, the correction for this term can be done by monitoring the temperature. The latter may occur due to gradual degradation of system performance (gain, loss, etc.) and/or failure of some active array elements. To monitor the latter term, an internal loop-back calibration function, transmitter power and receiver gain monitors have been implemented. To conduct an absolute calibration and to detect changes in antenna characteristics and telemetry sensors, a calibration scheme using an external reference target has also been developed.

An internal calibration algorithm has been developed using a detailed PR system model that describes the temperature dependence of all system parameters related to the conversion process from count value to the radar received power or to the radar reflectivity factor. The internal calibration handles the relative intermediate-term variation and some part of the long-term variation through the measurement of the input-output characteristics of the receiver.

External calibration of the PR, which handles the absolute calibration and monitoring the long-term variation, is performed using an Active Radar Calibrator (ARC) placed at a ground calibration site in Japan. An error budget analysis of the ARC calibration, including the error in the internal calibration, has indicated that the absolute calibration accuracy of less than 1 dBz could be achieved.

4.1.2.2 Calibration results

In the initial checkout of the PR, which was conducted for 2 months after the TRMM launch, the PR system gain was determined through ARC calibrations. 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 change 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 gain initially corrected. Sea surface return levels measured with the incidence angles between 6 and 10 degrees, known as most insensitive to surface roughness, are quite consistent with previous measurements by Ku-band airborne radars developed by JPL and CRL, and have been also 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 (Iguchi et al., 1998) and by the MU radar of Kyoto University show excellent agreements (differences within about 1 dB, on average; Sato et al., 1999). Those calibration and validation results indicate that the PR system characteristics are sufficiently stable and accurate to assure quantitative radar reflectivity surface radar cross-section measurements

4.1.3 VIRS

The VIRS radiometric calibration algorithm converts the digital data downlinked from the instrument into spectral radiances. VIRS has five bands, one in the visible, one in the shortwave infrared, and three in the thermal infrared. The calibration algorithm treats each band in the same manner; except that the visible and short wave infrared bands do not respond to the thermal radiation emitted by the instrument and these bands do not have the nonlinear responses with input radiance found in the thermal bands. 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.

The uncertainties of the VIRS radiances from the visible and Short Wave InfraRed (SWIR) bands are calculated to be 6%. The uncertainties for the thermal band radiances are approximately 3%, half those for the visible and SWIR bands. In terms of temperature, the uncertainties are about 2K at 300K. The uncertainty in the radiance from the onboard blackbody, combined with the uncertainty in the linearity of the response of the detectors, accounts for 2% of the total. 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 some low-light conditions, Channel 2 (1.6 microns) has some error, which is being corrected. The use of the on-orbit values does not remove the mirror as a primary source of uncertainty for the VIRS thermal radiances.

4.2 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. [1] From these comparisons and other information, Smith[2] developed an improved (versus "at launch") algorithm combining the PR and TMI together (called TCI in Figure 4.2.1). In this algorithm, the TMI is used to constrain the radar equation. Improvements were also made in the TMI vertical-profiling algorithm (GPROF).[3] Figure 4.2.1 shows the zonal ocean average rain rate for February 1998 as obtained by six different improved algorithms which will be used in the October 1999 product recalculation by TSDIS. The agreement in Fig. 4.3 is better than expected at this stage of the mission, as was the somewhat lesser agreement among the "at launch" algorithms. There remain discrepancies between the PR and other algorithms at the equatorial peak and midlatitudes, which are under investigation.

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

[2] Eric Smith, University of Alabama at Huntsville, personal communication.

[3] Ye Hong, personal communication.

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

To increase credibility of the TRMM products 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.

4.3.1 Climatological Validation

Table 4.3.1-1 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 long 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 4.3.1-1. 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 (Amitai, 1999; Marks et al., 1999), 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 (Kulie et al., 1999: Robinson et al., 1999; Marks et al., 1999).

Rain maps are generated from each of the primary sites following Steiner et al. (1995). 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 3B43. This is the one that uses TRMM results to adjust the Global Precipitation Index from geosynchronous satellites (see Section 5.1). The monthly rain estimates agree to within 20% for all of the sites with GV consistently estimating less rainfall. 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 to when the radars are operating, in which the monthly GV and satellite rainfall estimates are expected to agree within 15%.

4.3.2 Physical Validation

Table 4.3.2-1 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 4.3.2-1. 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 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
TEFLUN-B (TExas-FLorida UNderflight Experiment)	Florida	2	2	P, S, R, D, T
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

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 between 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 contained 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.

4.3.3 Summary of Ground Validation of TRMM rain products using "at launch" algorithms

The results of the first stage of ground validation are extremely encouraging, in that the pre-launch Science Team had envisaged that this agreement might be at first unsatisfactory, at least until the space data had been processed with the first improvement of the algorithms.

5. Early Applications to science

5.1 Comparison of El Niño/La Nina

As discussed above, the TRMM data by themselves provide a uniquely accurate rainfall data set. This makes it 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; Arkin and Meisner, 1987) assigns a single rain rate to all pixels colder than a specified temperature threshold. Adler et al. (1993, 1994) 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. (1997). 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 (5x5 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 Huffman (1997). The satellite/gauge estimate is 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 5.1.1 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.

5.2 The improvement of SSM/I products

The TRMM passive microwave algorithms provide an instantaneous product as well as a monthly aggregation. These algorithms were described in section 3. Since both products are physically based, the improved algorithms resulting from the continuous intercomparisons with the TRMM radar can also be immediately applied to the previous microwave observations such as those of the Special Sensor Microwave/Imager. This allows the knowledge gained from TRMM to be applied to data going back at least until 1987 which marked the launch of the first SSM/I instrument.

5.3 Tropical Cyclones: New views

5.3.1 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.

5.3.2 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 5.3.2.1). 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. PAKA was a mature Typhoon until December 22, crossing the entire North Pacific. She caused great damage at Guam and became a Supertyphoon shortly thereafter.

The first rapid deepening has been studied and related to a combination of the convective burst's carrying up high energy air (Halverson et al., 1999) and the storm core moving over warmer water (Rodgers et al, 1999).

5.3.3 Atlantic Hurricane studies

A cooperative hurricane field program, with four instrumented aircraft, coastal radars and special soundings, was undertaken in the season of 1998. The U.S. Weather Research Program focussed particularly on landfalling hurricanes. Three of these were penetrated many times by the aircraft, which carried both remote and in situ instruments. An important addition to the aircraft, geosynchronous and TRMM data set was the presence of an AMSU (Advanced Microwave Sounding Unit) on NOAA 15. An AMSU channel was able to detect the temperature and location of the hurricane warm core at a horizontal resolution of about 50-km. Combining AMSU with TRMM data on the many coinciding overviews will permit testing the hypothesis relating convective bursts to intensification via the warm core.

5.4 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 but employs moisture analysis increments instead of the initial condition as the control variable (see Hou et al., 1999, for details of the algorithm).

In assimilation experiments in which the 6-hr averaged GPROF rainfall (Kummerow et al. 19??) and Wentz's TPW retrievals (Wentz, 1999) 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 5.9).

Figure 5.4.1 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 percent reductions in error standard deviation (std dev) increase by about 20 per cent each 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. The improved analysis also improves short-range forecasts in the tropics but these improvements 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.

5.5 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. (1999 a, b) 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, Krishnamurti, et. al. 1991) 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. (1996)
c) Olson algorithm, Olson et. al. (1991)
d) Ferraro algorithm, Ferraro and Marks (1995)
e) TRMM 2 A12 algorithm, Kummerow et. al. (1996)
f) Contribution from TRMM 2 A12 plus the Ferraro algorithm.

Basically what we do is 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 are the best measures. Those are the TRMM 2A12 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. This entire data generated from the multi-analysis based forecasts and these '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. These are three-day forecasts 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 it ends up demonstrating is that much improved rainfall forecasts are now possible from 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, Treadon (1996), when we used physical initialization and SSM/I based rain rates, estimated from Olson et. al. (1990) algorithm. Fig (5.5.1) illustrates a past skill, i.e. the correlation of predicted and observed rainfall, plotted against the forecast days. This illustration is based on Treadon (1996). 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. Fig. (5.5.2) 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 (5.5.3 a, b, c) we show examples of rainfall forecasts on day 3 of forecasts, compared to the observed TRMM-based estimates at correlation levels of around 0.7 at day 3. This is a major accomplishment from the use of TRMM satellite data.

5.6. 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 Fig 5.6.1. It can be seen that the patterns of rainfall diurnal variability from different algorithms are similar. For "at launch" an algorithm, the agreement between the three is remarkably good. The dominant feature of rainfall diurnal cycle over ocean is that there is consistent rainfall peak in early morning, while there is 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 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 early-morning peak in winter, while both early-morning and late-afternoon peaks occur in summer and fall. Therefore, tropical rainfall has clearly diurnal phenomena, which is associated with large-scale convection. The diurnal variability has spatial and seasonal characteristics.

5.7 The effects of improved rainfall measurements on understanding the upper ocean layers and the El Niño/Southern Oscillation[4]

Even as one of the strongest warm ENSO events was underway in the Pacific Ocean in 1997, during the fall the Indian Ocean experienced an anomalous event with an eastern equatorial cooling of over 3°C 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 (Murtugudde and Busalacchi 1999). During fall 1997, along-shore 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 (Murtugudde et al. 1999). 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 (Birkett et al. 1999). 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 OGCM. The increase of over 500% in some regions was accurately captured by TRMM, which clearly improves the OGCM 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.

5.8. A sample LIS result

Figure 5.8.1 is one of many examples of how lightning records are valuable in indicating the presence or probable absence of strong convection. On the left, showing the region of the Hawaiian Islands, lightning is only seen over the islands themselves. This is logical

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[4] The work described in Section 5.7 was carried out by Dr. R. Murtugudde and colleagues of the Goddard

since on normal days, the trade-wind inversion restricts cloud development over the ocean; the only mixed-phase clouds are found over the mountainous islands where the updrafts are strong enough to break through the inversion. If lightning is found over water, the presence of a strong weather disturbance may be inferred. The left panel shows how the lightning record shows that a strong squall line is moving over the peninsula with strong clouds extending over nearby waters. To further understand the value of LIS, Figure 5.8.1 shows how the wider LIS swath enables detection of strong convection outside the narrow radar swath.

5.9 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. (1999) 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 (Wielicki et al., 1999). Figure 5.9.1 shows the tropical

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Laboratory for Oceans/NASA.

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 (Wong et al., 1999) 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.

5.10. 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.[5] 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 Super Ensemble methods described in Section 5.5 are used. Forecasts have been made. 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.

6.0 The Global Precipitation Mission

The transient nature of rainfall makes the detection of subtle changes difficult. The successful launch and early operation of the joint US/Japan TRMM mission will yield the first systematic maps of global rainfall and the distribution of latent heating. The TRMM radar and radiometer, used in combination, are able to limit the assumptions about drop-size-distributions, which permeate virtually all-global rainfall estimates. A second important result from TRMM will be its ability to improve the physical models serving as the basis for rainfall retrieval methods (from both ground and space). This improved

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[5] Work in progress. Person communication from Dr. P. Bauer at DLR, Germany

understanding will have an immediate positive feedback upon radiometer-only algorithms which in turn will allow for a reassessment of the climatic rainfall record for the last ten years (from SSM/I) and into the future (from AMSR), as we enter the EOS era. In addition to the expected advances in measurement and interpretation, the TRMM Precipitation Radar is also demonstrating that it is perhaps superior to ground-based systems in many regards. With an absolute calibration standard overflying local radars every three days or so, it will be possible to overcome the calibration problems that have plagued ground based radars since their inception. Rainfall information has also been shown to lead to dramatic improvements into assimilated data sets and and forecast models.

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. Moreover, the 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. The specific questions that will be addressed by this observing system can be summarized as follows:

- How are the rainfall and rainfall structure responding to changes in the Earth's temperature and other climate variables and do we understand this response?
- How directly is the surface hydrology coupled to the rainfall/evaporation and do we understand the relationship well enough to be of predictive value?
- What is the effect of rainfall over the oceans upon the ocean/atmosphere energy exchange and feedback mechanisms and can we understand this feedback?

In addition, the proposed observing system would have some immediate practical applications:

- As a calibration standard for ground based radars
- As input for data assimilation and weather forecast models
- For the global tracking of precipitation for severe weather forecasting, planning of human activities, flash flood warning and monitoring of communication satellite broadcast interference regions.

6.2 Measurement Approach and Specific Objectives

The next millennium will see a number of passive microwave radiometers launched on various platforms that measure some aspects of precipitation. The US will launch AMSR-E on its EOS-PM platform. AMSR will also be a component of the Japanese ADEOS-II satellite. Over the longer term, the NPOESS satellite series is designed to carry microwave radiometers. The prevalence of microwave radiometers in so many of these future missions is probably the best testimonial to the high benefit to cost ratio offered by these sensors. Over the oceans, these radiometers can accurately quantify surface temperature and wind speed, integrated water vapor, cloud water content and precipitation. Over land, the high frequency channels have a demonstrated ability to delineate and quantify convective precipitation through the detection of large ice particles in most storm systems.

These missions alone, however, cannot provide answers to the fundamental questions outlined above. For individual radiometers to properly infer the instantaneous rain rate at a given location, a series of assumptions about the vertical precipitation structure, drop size distributions and small-scale spatial variability of rain must be made. The TRMM mission is helping to quantify rainfall structure, drop size distributions and spatial variability. It cannot, however, detect changes in these variables after its mission ends in the year 2001. If we are to understand the consequences and feedbacks of global climate change upon rainfall and its associated latent heating patterns, we need to continue making detailed measurements of storm structures rather than relying upon proxy variables available from the EOS and NPOESS missions. Proxy variables cannot detect changes in the nature of the precipitation itself, which may lead to wrong conclusions. These future missions also do not provide the high frequency sampling needed to initialize hydrologic and agricultural output models; flash flood and tropical cyclone intensity forecasts, or even numerical weather prediction models.

The concept formulated by NASDA, therefore, is a two pronged approach. The primary, or core observatory will be a single, enhanced TRMM-like satellite that can quantify the 3D spatial distributions of precipitation and its associated latent heat release. This primary observation platform will be complemented by a constellation of very small, very inexpensive drones that sample the rainfall with sufficient frequency to be not only of climate interest, but which also have a local, short-term impact by providing rapid global rainfall coverage at 3 h intervals.

The technology of the primary observatory will be augmented, beyond what has been done with TRMM, by the addition of a second frequency radar, which ideally should have Doppler capabilities. Given the remarkable sensitivity of the TRMM 14 GHz radar (17 dBZ), it seems logical to extend these measurements into the future. The second frequency, intended to be 35 GHz, is extremely valuable because such dual frequency systems allow for the direct determination of the mean drop sizes, which affect the radar backscatter. With this system it should be possible to estimate the mean drop diameter to within 5% which results in a surface rainfall uncertainty of approximately 15% for a single pixel and a 1% for a typical rain system. The higher frequency radar further provides higher sensitivity to small hydrometeor concentrations thereby allowing for a more complete description of the entire column of hydrometers. This, in turn, provides much more accurate latent heat retrievals.

In addition to the dual frequency radar, the main observatory will carry a passive microwave sensor to serve primarily as a transfer standard to the constellation of small radiometers as well as the AMSR and AMSR-E radiometers planned for ADEOS-II and EOS-PM respectively. The technology for the radiometer is available today. It should be noted that the main observatory corresponds fairly closely to the Japanese ATMOS-A1 mission, indicating the strong collaborative potential for this satellite. The core satellite is envisioned to be in an inclined orbit (~ 70°) at an altitude of 400 km. The orbit will precess through the diurnal cycle much like TRMM.

The small radiometer mission, or drones, 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. To meet the science objectives stated above, the sampling error should be reduced to approximately 10% for daily rainfall accumulations. Moreover, the drones must be very small, light, and low on energy consumption. The primary cost driver for these satellites will be the satellite bus and launch vehicle. By keeping this instrument small and light, the cost of launching individual constellation satellites will be kept affordable.

The drone satellites are envisioned to be in polar, sun-synchronous orbits. Not only do these orbits afford the most effective way to sample the globe with a fixed repeat time, such orbits also make it possible to immediately take advantage of already available radiometer data such as the SSM/Is, AMSRs and NPOESS radiometers of the future. Without contributions from existing platforms, 8 drone satellites will be needed to achieve 3 hourly sampling. The precession rate is such that it takes 2 satellites to completely fill any 3-hour window and not leave gaps between orbits. The number of drones, however, can be immediately reduced once the number of existing radiometers is factored in. Currently, there are 2 SSM/Is in orbit that can take the place of these drone satellites. In the future, there might be as many as four satellites (3 NPOESS and 1 AMSR) in orbit.

International cooperation will play an important role in the proposed mission. Japan, following in the TRMM tradition, has expressed strong interest to partner with the United States in a follow-on study. The primary satellite should clearly be pursued as a joint US/Japan effort similar to TRMM. The drones, while still requiring some technology demonstration, obviously lend themselves to international cooperation on an unprecedented scale. By keeping the cost of each drone satellite below $40M, including the sensor, spacecraft, and launch vehicle, these satellites offer the opportunity to a large number of nations that cannot afford large EOS-type satellites to help improve their regional weather monitoring capabilities while at the same time contribute to global change research.

Eight satellites would be needed to establish 3-h average sampling intervals. Uncertainties due to sampling are shown in figure 1, as a function of domain size and sampling frequency.

7. Concluding Remarks

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 2.1. A major impact of the mission will clearly be the long-run improvements of the global weather and climate models consequent upon assimilation of correct 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 the better-than-expected precipitation results and the many other uses of TRMM data. The need for the continuation and extension to high latitudes of these measurements is apparent.

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Figure Captions

Fig. 2.2.1 Schematic view of the TRMM spacecraft and the scanning patterns of the three rain instruments black and white

Fig. 4.2.1 Comparison of TRMM products for February 1998, oceans only. Precipitation rate is plotted as a function of latitude. How each product is obtained is explained in detail in Section 3 with the identification number except GPCP which stands for the infra-red empirical algorithm used with geosynchronous IR imagery by the Global Precipitation Climatology Project. Color

Figure 5.1.1 Selected months in 1998 of Satellite/Gauge estimates of global rainfall, in transition from an El Niño to a La Niña pattern. See Section 5.1 and 3. 2 in text. Color

Figure 5.3.2.1. Geosynchronous and TRMM imagery of early stage of STY 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. color

Figure 5.3.2.2. 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 in warming suggesting a warming contribution by the anvils, a fairly common feature of typhoons and hurricanes. Courtesy of W. Olson.

Figure 5.4.1. NASA GEOS assimilation results with and without TMI observations for January 1998. The panel on the left shows errors in the monthly-mean tropical precipitation, total precipitable water, outgoing longwave radiation, and outgoing shortwave radiation in the GEOS control assimilation. The panel on the right shows the impact of assimilating TMI rainfall and TPW observations on these fields. The percentage changes relative to errors in the GEOS control are given in parentheses. See Section 5.4 for discussion. Color preferred.

Fig.5.5.1. Skill of the precipitation forecasts over global Tropics, (30°S to 30°N). Abscissa shows dates of forecast. For control forecast, physical initialization is using TRMM data only. Superensemble forecasts use TRMM plus SSM/I rain rates as a benchmark. Black and white

Fig.5.5.2. Comparison (in units mm day^{-1}) of observed rainfall (based on TRMM and SSM/I) on top and below the day 3 forecast for tropical Africa from the superensemble: Forecast valid for August 5, 1998 12 UTC.

5.6.1. 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

Fig. 5.8.1. Lightning activity as sensed by the LIS instrument on TRMM. Left: Hawaiian Islands region on an undisturbed day. Right: A squall moving down the Florida Peninsula.

Fig.5.9.1 Time Series of CERES/TRMM and ERBE/ERBS Scanner 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
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
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
Mbyte	megabyte
MHz	Megahertz
MU	
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency (of Japan)
NCEP	National Center for Environmental Prediction
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
SSM/I	Special Sensor Microwave/Imager
T_b	Brightness Temperature
TCI	TRMM Combined Instrument (algorithm 2B-31))
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	Reflectivity (must be defined in text)