THE STATUS OF THE TROPICAL RAINFALL MEASURING MISSION

C. Kummerow
Department of Atmospheric Science
Colorado State University
Fort Collins, CO, USA

Abstract: The Tropical Rainfall Measuring Mission (TRMM) satellite was launched on November 27, 1997, and data from all the instruments first became available approximately 30 days after launch. Since then, much progress has been made in the calibration of the sensors, the improvement of the rainfall algorithms and applications of these results to areas such as data assimilation and model initialization. The TRMM Microwave Imager (TMI) calibration has been corrected and verified to account for a loss of aluminum coating on the reflector surface. The Precipitation Radar (PR) calibration has been adjusted upward slightly (by 0.6 dBZ) to better match ground reference targets, while the Visible and Infrared Sensor (VIRS) calibration remains largely unchanged after launch. The improvements to the rainfall algorithms that were undertaken after launch are presented and intercomparisons of these products (Version 5) show agreement at the 20% level for global tropical monthly averages. The ground-based radar rainfall product generation is discussed. Quality control issues have delayed the routine production of these products but comparisons of TRMM products with early versions of the ground validation products as well as with rain gauge network data suggest that uncertainties among the TRMM algorithms are of approximately the same magnitude as differences between TRMM products and ground-based rainfall estimates. Finally, the TRMM field experiment program is discussed to describe active areas of measurements and plans to use these data for further algorithm improvements. The discussion ends with a look at a future precipitation mission now being discussed by a number of Space Agencies.

1. TRMM HISTORY

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. Precipitation, unfortunately, is one of the most difficult atmospheric parameters to measure because of the large variations in space and time. Tropical rainfall oscillates wildly between severe droughts and occasional deadly floods. Yet, it often lasts no longer than a few hours at a time. Until the end of 1997, precipitation in the global tropics was still very uncertain with large numbers of infrared and passive microwave algorithms providing very diverse estimates. Regarding "global warming", the various large-scale models differed among themselves in the predicted magnitude of the warming, distribution and amount of tropical precipitation, and in the expected regional effects of these temperature and moisture changes. Accurate estimates of tropical precipitation were desperately needed in order to validate and gain confidence in these models.

The idea of measuring rainfall from space using a combined instrument complement of passive and active microwave (radar) instruments was generated in the early 1980's. By September 1984, a proposal entitled "Tropical Rain Measuring Mission" was submitted to NASA Headquarters by a team of Goddard investigators. By November of 1985, the first major workshop was convened near Goddard to further develop the proposed "Tropical Rainfall Measuring Mission". Many participants from this meeting soon organized into a more formal Science Steering Group, which released a report establishing the science priorities for a mission in 1986. These goals are given in Table 1.

Table 1: TRMM goals established by the Science Steering Group in 1986.

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 oscillations in the tropics.

V. To help understand the effect that rainfall has on the ocean thermohaline circulations and 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.

To meet these objectives, the mission was to carry a precipitation radar, a multi-channel dual polarized, conically scanning passive microwave instrument similar to SSM/I, and a Visible/Infrared radiometer similar to the AVHRR. The purpose of the Visible/Infrared instrument was to enable TRMM to establish the connection between TRMM and operational geostationary platforms and thus serve as a "flying rain gauge".

In 1986, the Japanese Space Commission accepted an invitation to jointly study the feasibility of TRMM. Agreements between the United States and Japan were formalized in 1988, leading to a new start for a joint U.S./Japan mission at that time. The Japanese agreed to provide the precipitation radar and a launch by their new HII Rocket. NASA would provide the spacecraft and the other rain sensing instruments. The satellite was successfully launched from Tanegashima Island on November 27, 1997. Current expectations are for TRMM to remain in orbit until approximately March 2004, when the fuel needed to maintain the low earth orbit is expected to be depleted.

2. TRMM INSTRUMENTS AND INSTRUMENT DATA

The final TRMM instrument complement is shown in Table 2. TRMM's Precipitation Radar (PR) is the first radar designed specifically for rainfall monitoring to operate from space. While its swath is relatively narrow and it suffers from the same uncertainties for rainfall estimation as ground-based radars, the TRMM PR has delivered an incredible wealth of detailed rain structure information. Examples include the studies of propagating rainfall structures across land and ocean by *Takayabu et al.* (1999), the direct observational evidence for the suppression of rainfall by smoke contaminated clouds done by *Rosenfeld* (2000), the improvement of passive microwave rainfall retrievals, and methods for potentially using PR as a reference standard to cross calibrate ground-based radars. The passive microwave instrument, TMI, aside from providing the highest resolution data available to date, also has been used to derive sea surface temperature by a number of investigators (e.g. *Wentz et al.*, 2000). The combination passive and active sensors has, in turn, allowed researchers to look into further constraining parameters such as the Drop-Size-Distribution (DSD), *Haddad et al.* (1997) or *Viltard et al.* (2000). The visible and infrared instrument, in turn, has been useful to relate the detailed TRMM observations to the more available data from geostationary satellite data. It also has played in a key role in interpreting early results from the CERES instrument.

Table 2: TRMM sensor summary - rain package.

Microwave Radiometer (TMI)	Radar (PR)	Visible/Infrared Radiometer (VIRS)
10.7, 19.3, 21.3, 37.0, 85.5GHz (dual polarized except for 21.3 V-only) 10x7 km FOV at 37 GHz	13.8 GHz 4.3 km footprint 250 m vertical res.	0.63, 1.61, 3.75, 10.8 and 12 μm @ 2.2 km resolution
Conically scanning (53° inc)	Cross-track scanning	Cross-track scanning
760 km swath	215 km swath	720 km swath

Additional Instruments belonging to the Earth Observing System: CERES (Cloud & Earth Radiant Energy System) & LIS (Lightning Imaging Sensor)

The instrument characteristics themselves are not treated here as they are described in detail in the available literature. The core TRMM instrument, PR, TMI and VIRS are described in (*Kummerow et al.*, 1998). The LIS instrument is described in (*Christian et al.*, 1992), and the CERES instrument is described by (*Lee et al.*, 1998). A detailed algorithm description and further references are provided in *Kummerow et al.* (2000). Table 3 summarizes the rainfall and supporting parameter algorithms.

Zonally averaged rainfall for the new versions of the algorithms (Version 5) for 1998 are shown in Fig. 1. The Version 5 results indicate a narrowing of the differences among the algorithms from their at-launch versions, with the range over the ocean decreasing to 18 mm/month (24%). Comparisons of TMI and PR products with surface-based rainfall estimates are discussed in the next section.

Table 3: TRMM Satellite Products

Name	Ref. No.	Purpose
Level 2 Data		
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.
Level 3 Data		
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 and ratio of this product with accumulation of 2A12 in overlap region.
TRMM and other satellites	3B42	Geostationary precipitation data calibrated by TRMM. Daily, 1° resolution.
TRMM and other data	3B43	TRMM, calibrated IR and gauge products – data merged into single rain product. Monthly, 1° resolution.

3. VALIDATION EFFORTS DURING THE FIRST TWO FLIGHT YEARS

The validation efforts of TRMM are separated into two categories. The first is the routine comparisons of TRMM satellite rainfall products to operational gauge networks and ground-based radar estimates from a number of cooperative radar sites. The second consists of a series of now completed field experiments around the globe designed to physically validate and, when necessary, improve the assumptions, both the spaceborne as well as the ground-based instrument algorithms. Because cloud dynamical models are used to convert the TRMM observables into latent heating estimates, the field experiments had the additional objective of obtaining data sets that could be used to initialize and verify these cloud-scale models in diverse meteorological regimes.

3.1 Climatological validation

Climatological rainfall validation is centered around four primary validation radar sites (Kwajalein atoll; Melbourne, FL; Houston, TX; and Darwin, Australia). The primary sites are described in detail on the TRMM web site under "validation". Radar and rain gauge data are provided on a continuous, routine basis to Goddard Space Flight Center. The exception is Darwin, in which data are received only during the 5-6 month long wet season. Products from five additional 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 at their home institutions.

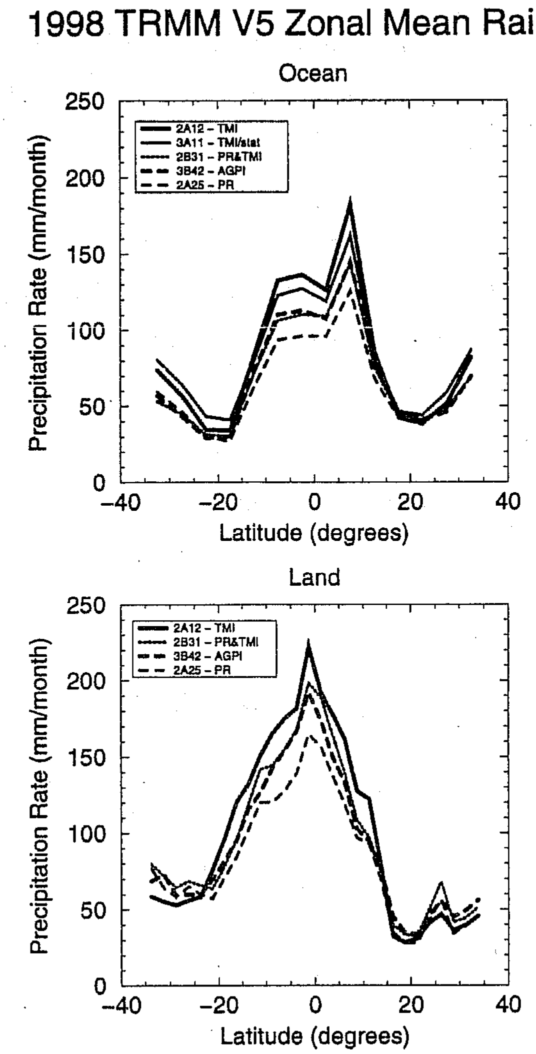

Fig. 1 Zonally averaged mean monthly rainfall for 1998 derived from five independent TRMM rainfall algorithms after the first substantial improvement cycle was implemented on Oct. 1, 1999 (Version 5).

Generating rainfall products that are of sufficient quality to validate climatological rainfall products from TRMM has been one of the key challenges for the Science Team. While high quality radar data sets exist for short periods, it has proven to be very difficult to extend those methodologies to routine operations based upon operational concepts. Data quality has proven to be the most difficult obstacle to overcome, with radar calibration being perhaps the most severe problem. A 1 or 2 dBZ calibration error can translate into error of up to 20% in the rainfall obtained from the application of standard Z-R relations. While progress has been made to use the TRMM radar itself as a calibration standard, the operational ground-based radar algorithms still use a bulk adjustment procedure to calibrate the monthly radar rainfall products to underlying rain gauge networks. Uncertainties produced by this technique are still being evaluated through the use of field experiment data.

Over oceans, initial comparisons of monthly rain estimates from TMI (2A-12) and PR (2A-25) have been carried out using estimates from Western Pacific Ocean atoll rain gauge data (*Morrissey and Greene*, 1991) as shown in Fig. 2. Although the scatter of points is large, due to both the sampling errors of TRMM and those of the sparse gauge coverage, the results indicate that the monthly estimates based on the TMI (2A-12) algorithm have an overall small negative bias (-9%) with a correlation of 0.86 when all atoll gauges are considered. The bias is +6% and the correlation increases to 0.91 when only grid boxes with two or more atoll gauges are considered. The monthly estimates based on the PR (2A-25) algorithm (Fig. 2b) show a much larger bias (-45%). The somewhat larger scatter of the PR estimates, especially at high rain amounts, may be due to the poorer sampling obtained from the PR's narrower swath.

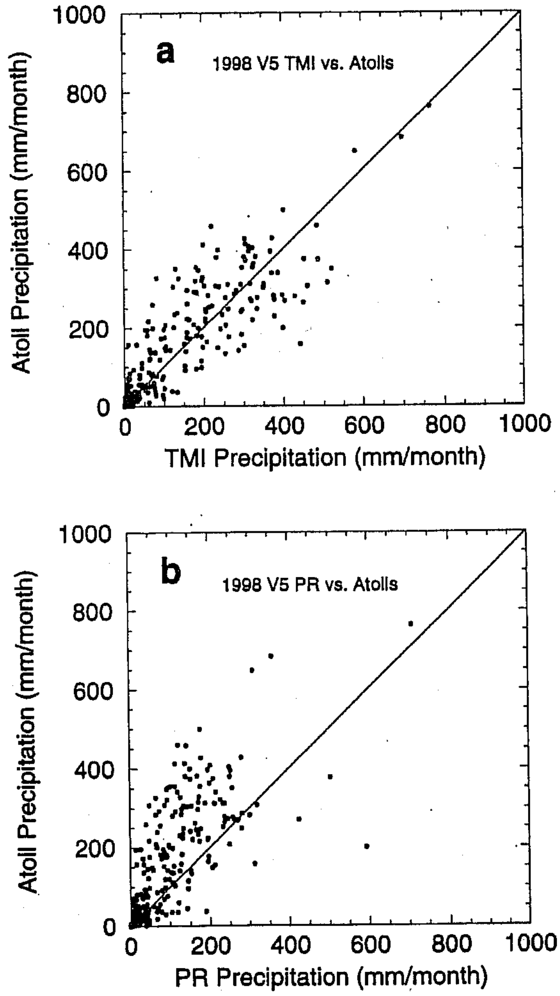

Fig. 2 Comparison of monthly TRMM rainfall estimates with monthly atoll rain gauge data. (a) passive microwave product (2A-12). (b) PR product (2A-25).

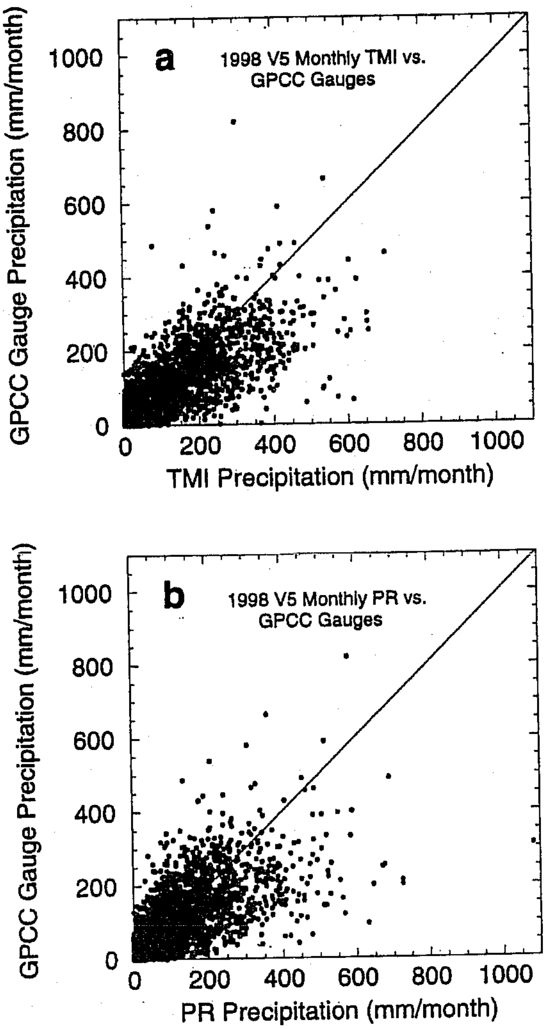

Fig. 3 Comparison of monthly TRMM rainfall estimates with monthly land rain gauge analysis. (a) passive microwave product (2A-12). (b) PR product (2A-25).

Over land the 1998, monthly estimates from TRMM were compared to a gauge-based analysis (*Rudolf et al.*, 1996) in locations (2.5° latitude/longitude boxes) where there are at least two gauges each month (Fig. 3). Although there is a large scatter of points due to the limited sampling in both the satellite and gauge analyses, the results indicate that both the TMI and PR algorithms have fairly small biases (+16% and +9%, respectively) over the range of the comparison data sets. Both algorithms may show a tendency toward overestimation in areas of high rain amounts, but that feature of the scatter could also be due to the unrepresentativeness in the gauge analysis at high values. The similarity between the TMI and PR results over land in Fig. 3 seems to disagree with the difference indicated in the zonal mean profiles of the various TRMM estimates in Fig. 1. This difference is due to the validation in Fig. 3 being restricted to areas where gauge information is available, thereby eliminating many of the high rain amount areas in South America, Africa, and elsewhere. The differences between the TMI and PR results are smaller outside of the heavy rain areas (see Fig. 1). Since these are the areas where the gauge analysis is useful for comparison, the results are biased toward lighter raining areas outside the deep tropics. Therefore, more detailed validation over land is required to fully understand the algorithm results in different climatological regimes.

In summary, the Version 5 TRMM products have converged substantially from the earlier, at-launch products, although there is still substantial differences over ocean and land. Preliminary comparison of TRMM results with existing gauge analyses over land and water indicate that, over water, the more mature TMI-based product compares well with atoll-based rain gauges, while the more experimental PR algorithm produces estimates significantly lower than the atoll gauges in the Western Pacific Ocean. Over land comparison of both TMI and PR products with gauge analyses produce favorable results with relatively small biases, but questions remain for important areas with high rain amounts that are not represented well in the gauge data sets.

3.2 Physical validation

While comparisons among spaceborne algorithms and ground-based products are useful to gain confidence in the various estimates, they cannot be used to reduce uncertainties below the uncertainty in the validation products. Quality control issues with the GV radar and gauge data sets indicate this is at least 10-15%. Five Field Experiments were conducted during the first two years of TRMM to address remaining issues. Table 4 lists the five different field experiments that were conducted during the first two years of the TRMM mission.

Table 4: 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	D, P, S, R, L
TEFLUN-B (TExas-FLorida UNderflight Experiment)	Florida	2	2	P, S, R, D, L
SCSMEX (South China Sea Monsoon Experiment)	South China Sea	2	0	S, R, D
TRMM-LBA (TRMM-Large Scale Biosphere-Atmosphere Experiment in Amazonia)	Rondonia, Brazil	2	2	P, S, R, D, T, L
KWAJEX (KWAJalein EXperiment)	Kwajalein, RMI	2	3	P, S, R, D, T

These experiments were designed to evaluate the assumptions made by rainfall retrieval algorithms and latent heating estimates made by both the TRMM sensors as well as the ground-based radars used for the routine validation. Because latent heating is not directly observable, the field experiments collected the necessary atmospheric profile information to initialize and validate the cloud resolving models being developed as an independent means of verifying latent heating estimates. 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. Three possible.

Three areas of possible discrepancy between radar and radiometer algorithms are being closely examined based upon the field experiment data. The first, being led by NASDA researchers, is the potential discrepancy between disdrometer derived DSD and the DSD actually sensed by the much larger footprint of the precipitation radar. The second, being led by NASA researchers, is the potential discrepancy between DSD derived from the PR and that inferred from the total absorption measured by TMI. The third, led by ESA investigators, is the potential error introduced in the TMI algorithm by the lack of a melting layer in both the passive microwave algorithms.

4. SUMMARY AND NEXT STEPS

Overall, the TRMM mission continues to perform very well. All instruments are operating as expected and have been calibrated to a level necessary for rainfall applications. No further calibrations, changes except those resulting from normal operations, are expected at this time. All rainfall products have been reprocessed through Version 5 on the satellite, while the ground validation products through Version 4 are expected in the summer of 2000. There are no problems with the satellite itself or the data system. Fuel, which is the limiting resource needed to maintain TRMM's low orbit, is expected to last until approximately March of 2004.

While much work remains to be done, the promising early results from the TRMM mission have led NASA to endorse a new concept for Global Precipitation Measurements. The concept is to address climate-rainfall variability and has been formulated with two components. A single primary satellite similar to TRMM but in a 70° inclination, that can quantify the 3-dimensional spatial distribution of precipitation and the associated latent heat release. This "core" platform would carry a dual frequency rain radar plus a multi-channel, polarized passive microwave radiometer akin to TMI. By use of two radar frequencies, it will be possible to determine the first moment of the drop size distribution (i.e., the DSD mode) and thus rainfall rates may well exceed the quality of standard ground-based weather radars. The radiometer, as is the case for TRMM, would provide further insights into cloud properties and cloud processes beyond that given by radar reflectivities alone, and would further serve to transfer knowledge gained by the core satellite to the swaths of complementary satellites that form the second component of the measurement concept. The second component consists of a number of small radiometer satellites (or microsats) flown in a constellation configuration, to provide the necessary diurnal sampling needed to force both hydrological and meteorological models. With a total of eight constellation radiometers, which could consist of a mixture of microsats and various operational satellites carrying passive microwave radiometers (such as SSM/I on DMSP and AMSR on ADEOS II or AQUA), a sampling frequency of 3 hours would be achieved. This reduces sampling uncertainties to below 10% for daily rainfall accumulations. As demonstrated with ongoing research related to TRMM, such measurements will have significant positive impacts on prognostic model data assimilation and weather forecasting skills, as well as on hydrological applications that require near continuous sampling.

5. REFERENCES

Christian, H.J., R.J. Blakeslee, and S.J. Goodman, 1992: Lightning imaging sensor (LIS) for the earth observing system. NASA TM-4350, Available from Center for Aerospace Information, P.O. Box 8757, Baltimore Washington International Airport, Baltimore, MD 21240, 44.

Haddad, Z.S., E.A. Smith, C.D. Kummerow, T. Iguchi, M.R. Farrar, S.L. Durden, M. Alves, and W.S. Olson, 1997: The TRMM "Day-1" radar/radiometer combined rain-profiling algorithm. J. Met. Soc. Japan, 75 (4), 799-809.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The tropical rainfall measuring mission (TRMM) sensor package. J. Atmos. and Ocean Tech., 15, 808-816.

Kummerow, C., J. Simpson, O. Thiele, W. Barnes, A.T.C. Chang, E. Stocker, R. F. Adler, A. Hou, R. Kakar, F. Wentz, P. Ashcroft, T. Kozu, Y. Hong, K. Okamoto, T. Iguchi, H. Kuroiwa, E. Im, Z. Haddad, G. Huffman, B. Ferrier, W. S. Olson, E. Zipser, E.A. Smith, T.T. Wilheit, G. North, and K. Nakamura, 2000: The status of the tropical rainfall measuring mission (TRMM) after 2 years in orbit. J. Appl. Meteorol., (accepted)

Lee, R.B, B.R. Barkstron, H.C. Bitting, D.A.H. Crommelynck, J. Paden, D.K. Pandey, K.J. Priestley, G.L. Smith, S. Thomas, K.L. Thornhill, and R.S. Wilson, 1998: Prelaunch calibrations of the CERES TRMM and EOS-AM1 spacecraft thermistor bolometer sensors. IEEE Trans. Geo. and Rem. Sens., 36, 1173-1185.

Morrissey, M.L. and J. S. Green, 1991: The Pacific Atoll Rain gauge Data Set. Planetary Geosci. Div. Contrib. 648, Univ. of Hawaii, Honolulu, HI, 45 pp.

Rosenfeld, D., 2000: Suppression of rain and snow by urban and industrial air. Science, 287, 1793-1796.

Rudolph, B., H. Hauschild, W. Ruth, and U. Schneider, 1996: Comparison of rain gauge analyses, satellite-based precipitation estimates, and forecast model results. Adv. Space Res., 18, 53-62.

Takayabu, Y. N., T. Iguchi, N. Kachi, A. Shibata, and H. Kanzawa, 1999: Abrupt termination of the 1997-98 El Niño in response to a Madden-Julian oscillation. Nature, 402, 6759, 279—282.

Viltard, N., C. Kummerow, W.S. Olson and Y. Hong, 1999: Combined use of the radar and radiometer of TRMM to estimate the influence of drop size distributions on rain retrievals. J. Appl. Meteor., (accepted).

Wentz, F., C. Gentemann, D. Smith, D. Chelton, 2000: Satellite measurements of sea-surface temperature through clouds. Science, 288, 847-850.