6.4 COMPARISON OF TRMM SATELLITE-BASED RAINFALL WITH SURFACE RADAR AND GAUGE INFORMATION

[1]T. Keenan*, E.Ebert[1], V. Chandrasekar[2], V. Bringi[2], and [1]M. Whimpey[1]

[1]Bureau of Meteorology Research Centre (BMRC), Melbourne, Australia
[2]Colorado State University, Fort Collins CO, USA

1. INTRODUCTION

A multi-scale approach to validation of Tropical Rainfall Measuring Mission (TRMM) products is examined employing data collected as part of Australian ground validation program. Basically a two pronged approach is employed: validation on the scale of the direct satellite measurements examining the vertical structure of radar reflectivity and rainfall as measured by the TRMM Precipitation Radar (Iguchi et al., 2000) and from the TRMM Microwave Imager (TMI), described by Kummerow et al., (1998); and on monthly time scales employing standard TRMM PR, TMI and combined rainfall products validated against the Australian national gauge analysis. Pre and post boast mission phases are included in this study.

2. DESCRIPTION OF DATA

TRMM products examined in this paper are summarised in Table 1. For validation of the TRMM Level-2 data, the C-Band Polarimetric (CPOL) radar described by Keenan et al. (1998) located at Darwin, Australia (12S 131 E) in a tropical monsoon environment are employed. Data from the seasons of 1999/2000 and 2001/2002 are used along with that collected as part of the South China Sea Monsoon Experiment (SCSMEX) conducted during May-June 1998**.**

TABLE 1 Summary of TRMM satellite products

Name	Code	Description
Level-2		
TMI	2A12	Surface Rainfall and 3D Structure
PR	2A25	Surface Rainfall and 3D Structure
PR-TMI	2B31	Surface Rainfall and 3D Structure
Level-2		
PR	3A25	Monthly 5^0 rainfall
PR	3A25hr	Monthly 0.5^0 rainfall
PR/TMI	3B31	Monthly rain accumulation
TRMM/ other	3B42m	Monthly 1° rain accumulation (Geostationary calibrated by TRMM)-sum of daily totals.

The CPOL measurements are subjected to the attenuation-correction procedures of Bringi et al. (2001). Polarimetric-based consistency checks described by Keenan (2003) imply that the CPOL Z_{HH} values have a variance of 0.5 dB compared to the "reference" values and the Z_{DR} values are internally consistent to about 0.2-0.3 dB during the periods studied. The polarimetric radar parameters Z_{HH}, Z_{DR}, K_{DP} and A_H are derived in raw radar space and and converted to a three dimensional Cartesian grid of 2.5 km resolution in the horizontal grid and 0.5 km resolution vertically "Hybrid" polarimetric radar rainfall estimators given in Table 2 are then derived using these fields.

Data from some forty-seven tipping bucket gauges located within 130 km of Darwin are employed to validate the Darwin CPOL radar rainfall estimates. The on-going performance of each gauge is closely monitored with thorough calibration tests. The gauge rainfall data are converted to three, five and eleven minute rain rates for the purposes of this study.

The Australian national rainfall analysis, described by Weymouth et al., (1999) is compared to the to the level 3 TRMM products. This analysis is on a 0.25^0 grid at 24 h resolution and is based on some 5000 gauges. A domain overlapping with the TRMM coverage is extracted for validation purposes.

TABLE 2 Summary of CPOL Rainfall Estimators

$R(K_{DP})=32.4K_{DP}^{0.85}$ for $Z_{HH}>35;K_{DP}>0.5$
else=$R(Z_{HH})$;

$R(K_{DP},Z_{DR})=60K_{DP}^{0.93}10^{0.24Z_{DR}}$ for $Z_{HH}>35;K_{DP}>1;Z_{DR}>1$
else =$R(K_{DP})$

$R(A_H,Z_{DR})=895A_H^{0.98}10^{0.3Z_{DR}}$ for $Z_{HH}>35;Z_{DR}>1$;
else =$312A_H^{0.86}$ for $Z_{HH}>35$; $A_H>0$
else=$R(Z_{HH})$;

$R(Z_{HH})=0.015(10^{Z_{HH}/10})^{0.734}$

$R(Z^{UC}_{HH})=0.015(10^{Z^{UC}_{HH}/10})^{0.734}$

Where Z_{HH}=attenuation corrected horizontal reflectivity and Z^{UC}_{HH}=uncorrected reflectivity

3.0 COMPARISON OF TRMM PRECIPITATION RADAR REFLECTIVITY WITH CPOL

Significant differences exist between the CPOL and the TRMM Precipitation Radar (PR) measurement process and they affect any inter comparison. Issues include differences in the frequency of operation (CPOL 5.6 GHz, PR 13.8 GHz), the sample volume (CPOL 300m, PR 4.3 km footprint), the geometrical viewing angles (CPOL horizontal, PR near vertical), attenuation, radar sensitivity (CPOL –29 dBZ, PR 17 dBZ) and potential calibration biases. To this end reflectivity characteristics of the CPOL radar and the TRMM PR radar are compared, following Bolen and Chandrasekar (2000) to account for the different view angles, beam widths etc of the two platforms. The TRMM PR is remapped to a 4 km horizontal grid from 1.5- 15 km at 0.25 km height intervals. Then the PR data are averaged linearly in the vertical at each grid point to match the CPOL beamwidth. CPOL data are

---

Corresponding author address: Dr T. Keenan, BMRC, GPO Box 1289K, Melbourne, Australia, 3001; email: T.Keenan@bom.gov.au

also mapped to a 0.5 km grid at each height and averaged horizontally to match the PR resolution. A coincident grid is then made for the PR and CPOL data enabling direct comparison of the CPOL and PR data.

TABLE 3 Comparison of CPOL and TRMM PR reflectivities

Date/Time	Bias (dB) 2-4 km (PR-CPOL)	dBZ_{max}/ Height (km)	Storm Top$^{\%}$ (km)	Type
	SCSMEX			
1998051601:30	-3.5	52.5/3	9	S.Conv
	DARWIN			
20000303 16:00	-0.8	43/2.5	6	W.Conv
20000303 16:00	-1.0	33/4	7	W.Conv
20000303 16:00	-1.5	47/2	6	Conv
2000030416:00	-0.6	47/2	7	W.Conv
20000314 01:04	-0.9	37/2.5	6	W.Conv
20000314 01:04	-3.2*	38/2.5	6	Conv/stf
20000314 01:04	0.5	43/3	7	Conv
2001110 09:07	-2.5	42.5/4.5	6.5	Stf
20011127 14:57	-6.5	57.5/2.5	13.5	S.Conv
20011127 14:57	-6.4	52.5/3.0	8	S.Conv
20011230 22:10	-3.3	42.5/4	8	S.Conv
20011212 07:34	-3.4	52.5/1.5	8.0	S.Conv
20011212 07:34	-1.1	37.5/4.5	6.0	Stf
20011212 07:34	-2.5	47.7/2	6	W.Conv
20011221 12:21	-0.9	37.5/5.0	7.0	Stf
20011230 22:05	-3.3	57.5/5.0	14.0	S.Conv
20020109 02:50	-3.7	52.5/4.5	15	S.Conv
20020109 02:50	-6.7	52.5/4.0	11	S.Conv
20020109 02:50	-4.7	52.5/5.0	10	S.Conv
20020110 09:29	-3.6	57.5/1.5	12.5	S.Conv
20020123 19:30	-2.4	42.5/5.0	7.0	W.Conv
20020123 19:30	-5.6	57.5/4.0	13.5	S.Conv
20020207 12:08	-6.4	52.5/5	9	S.Conv
20020211 10:04	-2.9	37.5/5.5	7.5	W.Conv

*small number of samples

$^{\%}$Height of 30-35 dB reflectivity averaged xtrack

Conv=Convection, stf=stratiform, s=strong, w=weak

A summary of reflectivity differences in rain (averaged over the 2-4 km height range) for CPOL and the PR 2A25 using the above technique shows considerable variability as indicated in Table 3. Differences range from -6.7 dB to +0.5dB with a mean difference of -3.2 dB (CPOL larger then PR). Greatest variability in the comparison occurs with strong convective phenomena, in the mixed phase region. The mean difference is -3.3dBZ in all convective cases compared to the -1.5 dBZ difference for the limited number of stratiform cases. The differences are somewhat larger than those reported by Bolen and Chandrasekar (2000).

4. COMPARISON OF LEVEL 2 TRMM AND CPOL RAINFALL STRUCTURE

To evaluate the accuracy of the various level 2 TRMM inferred rain rates CPOL data are employed herein. First the accuracy of CPOL rainfall algorithms is evaluated by comparison with Darwin gauges. The results for the various algorithms are summarised in Fig.1 using a Taylor (2001) diagram. This approach enables evaluation of how much the root mean square (RMS) difference in the gauge and radar-derived values is attributable to differences in variance and differences in correlation, given the two parameters provide complementary statistical information. In Fig. 1, a reference field (gauge) standard deviation is plotted along the abscissa and standard deviation of the test field (radar estimate) is plotted along a radial but at an angle corresponding to the cosine of the correlation between the two fields. In this case, the standard deviations have been normalized by the gauge value. In the context of this diagram, the distance from the reference abscissa value of one (solid circle), to each point represents the centred pattern RMS difference. Ideally, the closer the values are to the reference point the better.

All radar estimators underestimate the variance of the gauge rain rates but have similar correlations (near 0.7). Hence the phasing of rain rate variations is similar with all five estimators but differences exist in the estimated amplitude of the rain rates.

Relative to the gauges $R(Z_{HH}^{UC})$ is clearly the least accurate estimator, followed by $R(Z_{HH})$. The "hybrid" polarimetric estimators $R(K_{DP}, Z_{DR})$ and $R(A_H, Z_{DR})$ are more accurate (closest vector distance to the reference location). In terms of bias, there is a 50% underestimation for $R(Z_{HH}^{UC})$ decreasing in magnitude to 35% for $R(Z_{HH})$ with the polarimetric $R(K_{DP})$, $R(K_{DP},Z_{DR})$ and $R(K_{DP},A_H)$ having biases in the range 23-27%.

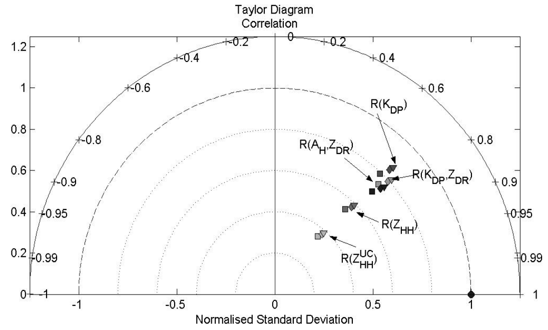

Figure 1. Taylor Diagram representation of CPOL rainfall estimation errors using three (square), five (diamond) and eleven (triangle) minute gauge rates.

A typical example of the correspondence between TRMM level 2 A12, 2A25 and 2B31 rain rates and CPOL data is shown in Fig. 2 for 21 November 2001, a case of leading convection and trailing stratiform precipitation. In this example a

CPOL 2.5 km resolution CAPPI at 2 km height is compared to TRMM surface rates (with the exception of the A25 where the 2 km height is employed). The variability in the instantaneous rain rates is considerable with CPOL biased 20-40% larger compared than the TRMM products. The 2A12 product does not reproduce the CPOL observed rain rate distribution particularly well. For 2A12, the frequency of low rain rates (< 5 mm h^{-1}) and high rain rates (> 40 mm h^{-1}) are underestimated and rates in the range 5-40 mm h^{-1} are overestimated compared to CPOL. The 2A25 and 2B31 rain rate distributions are better matched with those of CPOL.

Examination of all overpass times during 2001-3 in Darwin indicates the 2B31 shows the best correspondence with CPOL, followed by the 2A25 product and then the 2A12. Median correlation coefficient/ median mean absolute error (mm h^{-1})/ median normalised bias (%) obtained by comparing the CPOL $R(K_{DP},Z_{DR})$ estimator at 1.5 km height with surface or equivalent height TRMM products obtained for all 200-2 overpasses are 0.54/3/8, 0.68/3.2/11, 0.3/7/52 for B31, A25 and A12 respectively.

5.0 COMPARISON OF TRMM MONTHLY PRODUCTS WITH GAUGE DATA

Variations in the monthly Australian area rainfall (in TRMM product overlap region) during the period 1998-2002 are summarised in Fig. 3 along with various level 3 TRMM products. The gauge observed rainfall is at a maximum during the southern summer when the total integrated rain volume increases by ~a factor of four over wintertime values. This is directly associated with increased rain area, and intensity reflecting the onset of convective activity during the Austral summer in part associated with the Australian summer monsoon. The estimates of various TRMM estimation techniques follow the same seasonal trend, reaching a maximum in the Austral summer.

All TRMM techniques overestimate the observed monthly rainfall with biases in the range 4-25%. This bias is more evident in summer. None of the techniques captured the extreme variations observed during the period February-May 2000. In terms of relative accuracy the 3A25hr performs least satisfactorily over continental Australia. It has the lowest correlation coefficient (0.2-0.4), a mean absolute (root mean square) error typically two (three) times larger than the alternate techniques.

As shown in Fig.3, the estimates can be noisy, with extreme values of monthly rainfall indicated at various times. These metrics reflect a failure by the 3A25hr to capture the observed spatial structure of the monthly rainfall. Insufficient TRMM passes to estimate rainfall on a 0.5^0 grid is probably the cause.

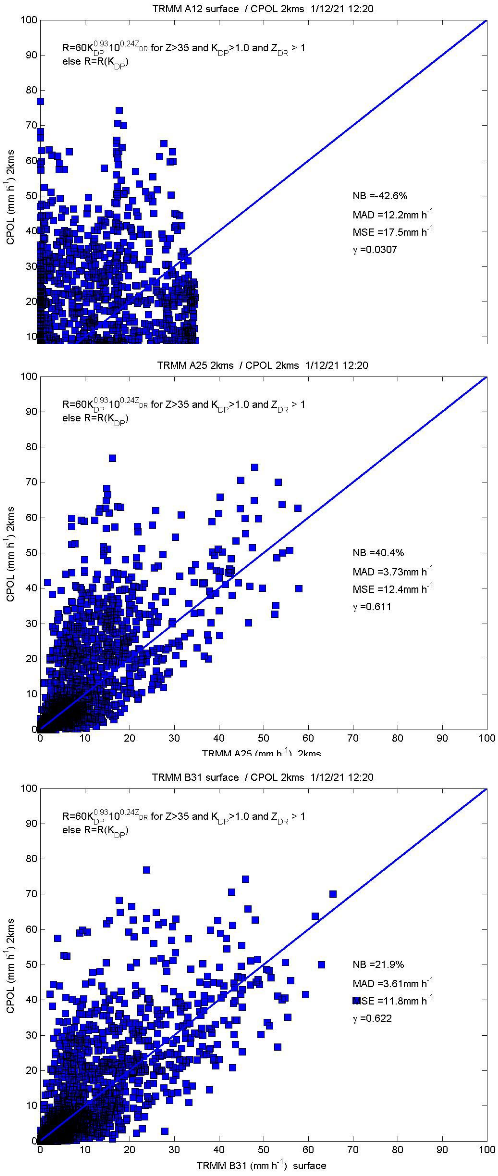

Figure. 2 Comparison of CPOL $R(K_{DP},Z_{DR})$ and TRMM level 2 rain rate products at Darwin for TRMM overpass on 21 December 2001.

The other TRMM techniques show similar performance to each other. From Fig.3, it is evident that the 3A25 and 3B31 show strong correspondence, tracking closely and generally better than 3B42 in winter and spring months. In this respect the use of the geostationary satellite data is having positive impact on the ability of the 3B42 techniques to capture summer convective rain episodes.

No strong trends are evident in estimates obtained the pre and post boast periods over Australia. Biases appear slightly higher post-boast with the exception of 3A25hr.

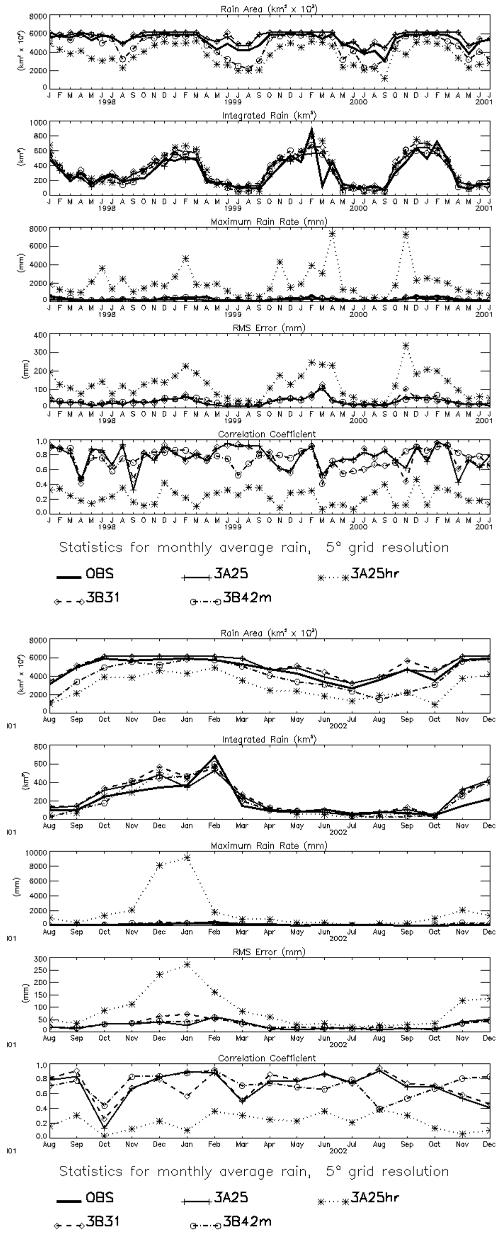

Figure 3 Comparison of monthly Level 3 TRMM products with Australian region rainfall.

6.0 SUMMARY

Comparison of TRMM products with Australian ground validation data has been undertaken on various scales encompassing the pre and post boast mission phases. There is no evidence for any systematic change in the calibration of TRMM products during these two phases.

Direct comparison of TRMM A25 reflectivity averaged over the 2-4 km height range is approximately 3dB lower than observed with CPOL. The variability is considerable especially during the majority of the convective events. If stratiform events only are considered the difference is only 1.5 dB.

Comparison of the TRMM level 2 rain products with CPOL derived rain products shows that the A25 and B31 products have good correspondence with CPOL estimates, although the higher resolution CPOL estimates are generally biased 10-20% higher than the combined 2B31 product.

On the monthly time scale, validating level 3 TRMM products against the Australian region rainfall gauge-based analysis (land-based only), a 4-25 % bias is evident in TRMM products (TRMM higher). This bias is typically manifested in summer situations presumably dominated by convective rainfall events

Acknowledgements

TRMM NRA-99-OES-03 supported this work

7.0 REFERENCES

Bolen, S. and V. Chandrasekar, 2000: Quantitative Cross Validation of Space-Based and Ground-Based Radar Observations, *J. App. Meteor.*, **39**, 2071-2079.

Bringi, V.N., T.D. Keenan and V. Chandrasekar, 2001: Correcting C-Band Radar Reflectivity and Differential Data for Rain Attenuation: A Self Consistent Method with Constraints. *IEEE Trans. Geoscience and Remote Sensing*, **39**, 1906-1915.

Iguchi, T , T. Kozu, R. Meneghini, J. Awaka and K. Okamoto: Rain-Profiling Algorithm for the TRMM Precipitation Radar. *J. App. Meteor.*, **39**, 2083-2052.

Keenan, T., K. Glasson, F. Cummings, T.S. Bird, J. Keeler and J. Lutz, 1998: The BMRC/NCAR C-Band Polarimetric (C-POL) Radar System. J. Atmos. and Oceanic Tech., **15**, 871-886.

Keenan, T., 2003: Hydrometeor classification with a C-band polarimetric radar, *Aust. Met. Mag.*, **52**, 23-31.

Kummerow, 2000: The status of TRMM after two year in orbit, *J. App. Meteor.,* **39**, 1965-1982

Weymouth, G., G.A. Mills, D. Jones, E.E. Ebert, and M.J. Manton, 1999: A continental-scale daily rainfall analysis system. *Aust. Met. Mag.*, **48**, 169-179.