TROPICAL RAINFALL-SURFACE TEMPERATURE RELATIONS USING TRMM PRECIPITATION DATA

Jian-Jian Wang[1], Robert F. Adler[2], Guojun Gu[1]

[1]UMBC/GEST; Mesoscale Atmospheric Processes Branch, NASA GSFC
Greenbelt, MD 20771
[2]Lab for Atmospheric Sciences, NASA GSFC

Abstract

In this study, nine-years (1998-2006) of monthly precipitation data from Tropical Rainfall Measuring Mission (TRMM) are used to examine the relations between tropical rainfall and surface temperature.

A technique is developed to adjust the PR monthly rainfall data in the Tropics (whole ocean and whole land) to account for the effect of the TRMM orbit boost from 350 km to 402 km in August 2001. The post-boost PR rainfall is adjusted by adding 6.5%, 6.0%, and 1.0% to the monthly PR rainfall data over the ocean at estimated surface, near surface, and 2km level, respectively. No adjustment is made for data over land or above the 4 km level.

Overall, it is found that the PR-based precipitation-temperature slopes do not confirm slopes based on passive microwave observations. This may be result of PR retrieval error, or inherent passive/active retrieval differences. Further research is needed to advance the use of TRMM data in this regard.

INTRODUCTION

Tropical convection and its associated precipitation is a key component to the Earth's water cycle. Long-term analyses of global precipitation data such as that from the Global Precipitation Climatology Project (GPCP) (Adler et al., 2003a) are used to investigate regional and global precipitation variations on time scales from seasonal to inter-decadal. Inter-annual variations in the Tropics are dominated by the El Niño-Southern Oscillation (ENSO) phenomenon, although its influence on precipitation patterns can be shown to have a global reach (Soden, 2000, Curtis and Adler, 2003).

In the Tropics, Gu et al. (2007) isolate the ENSO precipitation signal and the signal related to volcanic aerosols, allowing a better examination of the remaining, long-term linear changes (i.e., trends) over the 1979-2005 period. These calculated linear changes show a 5% increase over tropical oceans during the 27-year period and a slight decrease over land resulting in a possible 4% increase over the Tropics as a whole. A similar increase in ocean precipitation has also been noted by Wentz et al. (2007) using passive microwave rain retrievals for a shorter period. This calculated precipitation increase is coincident with increased ocean temperatures. The GPCP inter-annual and long-term precipitation changes are primarily driven by information based on SSM/I (Special Sensor Microwave/Imager) data on polar-orbiting satellites (for a full description of GPCP data and techniques see Adler et al., 2003a). Passive microwave retrievals over the ocean require information about the depth of the rain column, which is usually tied to the height of the 0°C isotherm, which in turn is correlated to surface temperature (e.g. Chiu and Chang 2000, Kummerow et al. 2001). Hence inter-annual or long-term rain-temperature relations using rain variations deduced from passive microwave observations must be used cautiously, since temperature information (directly or indirectly) is necessary for the rain retrievals. With the launch of the Tropical Rainfall Measuring Mission (TRMM, Simpson 1988; Kummerow et al. 2000) satellite in late 1997, it is now possible to examine variations in rainfall with information from both the TRMM Microwave Imager (TMI) [passive microwave] and the TRMM Precipitation Radar (PR), albeit for a relatively short period (< 10 years). Rain retrievals based on the PR are independent of surface or tropospheric temperature. The objective of this research is to examine surface temperature-precipitation relations over the Tropics with both the active and passive microwave sensors on TRMM and compare the results to GPCP-based calculations to seek confirmation of these relations.

ADJUSTMENT OF PR RAIN ESTIMATES FOR IMPACT OF ORBIT BOOST

Before the PR rain estimates for the entire nine-year period can be used in this analysis the impact of the TRMM orbit boost from 350 km to 402 km altitude in 2001 must be taken into account. The effect of the boost can be seen in Fig. 1, where the time series of PR monthly rainfall data relative to the monthly GPCP rainfall for the latitude band 25°N-25°S is plotted. Because the GPCP is only the surface rain estimate and the different PR products are at different altitudes with a general decrease with height, the important value is the change in the offset from before to after the boost. The GPCP analysis does not contain TRMM data and is therefore independent of the boost effects. There is an apparent drop of PR rainfall data at the lower levels (especially at ES and NS levels, Fig. 1a) since August 2001, when TRMM's orbit was raised to extend the mission's life. It is also noticed that this drop of the PR rainfall amount during the post-boost period is less obvious at 2 km, with only about one-half of the decrease at the surface. At the 4 km and 6 km levels, the difference between TRMM 3A25 and GPCP remains about the same from pre-boost to post-boost period (Fig. 1b). This result is also in consistent with the studies by Robertson et al. (2007). Table 1 gives the shift in the mean values from before to after the boost (relative to GPCP). The PR ES value drops .28 mm/d. Relative to the pre-boost mean PR ES value (2.6 mm/d) this is a drop of over 10%. This is a significant drop and must be taken into account when using the PR data for careful inter-annual studies.

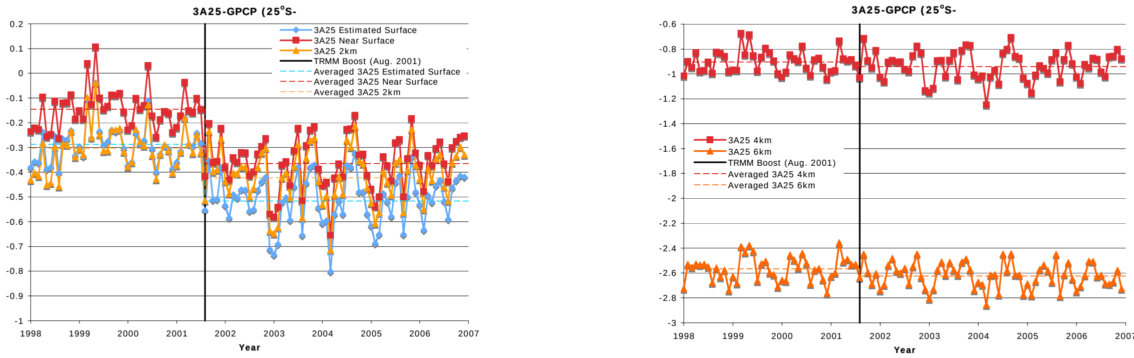


Fig.1 Time series of the difference between PR (3A25) and GPCP monthly rainfall data at selected levels. The solid black line indicates the time when TRMM satellite raised its orbit.

Table 1 The mean differences (mm/d) from TRMM PR rainfall measurements to GPCP before and after the boost of TRMM satellite

	1/98-8/01	9/02-12/06
Estimated Surface	0.19	0.47
Near Surface	0.07	0.34
2 km	0.24	0.38
4 km	1.03	1.09
6 km	2.59	2.71

Takahashi and Iguchi (2004) state that the effect of the TRMM orbit boost on the PR data may include: a) the degradation of the radar sensitivity by about 1.2 dB due to the larger distance from satellite to rain target and 2) a mismatch between the transmission and reception angles for one pulse from among 32 pulses. Using PR nadir data, Kwiatkowski et al. (2007) suggested that the increased thickness of clutter region due to the orbit boost may be the main factor is that responsible for the decrease of PR rain near the surface.

In this study, we first develop a simple and robust technique for adjusting the PR monthly rainfall data in Tropics (whole ocean and whole land) during the post-boost period to make PR rainfall data a homogenous dataset. The basis for the adjustment approach is that there are two main factors influencing the estimated monthly ocean (and land) TRMM PR retrievals. The first is the impact of the orbit boost as already described. The second is the relationship between the tropical ocean (and land) rainfall and ENSO events (e.g. Soden 2000; Gu et al., 2007). Ocean and land are treated separately because of small but significant differences in PR retrievals over land and ocean and also differences in the TMI-based rain retrievals between ocean and land. In this exercise, the Nino3.4 index will be used as an indicator of ENSO events. Nino3.4 is the average sea surface temperature anomaly in the region bounded by 5°N to 5°S, from 170°W to 120°W, which is the region with most intense variability on interannual/El Niño time scales.

To study the relationship between monthly rainfall anomaly and Nino3.4 index, the seasonal variation of rainfall is removed. Ideally, a complete 12 monthly climatology of rainfall throughout the 9-year (1998-2006) TRMM period would be calculated as the mean state. However, since the 9-year averaged PR data contains both pre-boost and post-boost periods, the GPCP rainfall data were selected for this purpose. The difference of the monthly TRMM PR rainfall from the GPCP climatology of rainfall is then treated as the monthly rainfall anomaly. The different relation between rainfall anomaly and Nino3.4 index for the pre-boost and post-boost periods of TRMM satellite will provide us the basis for adjusting the post-boost period monthly rainfall for tropical ocean and land.

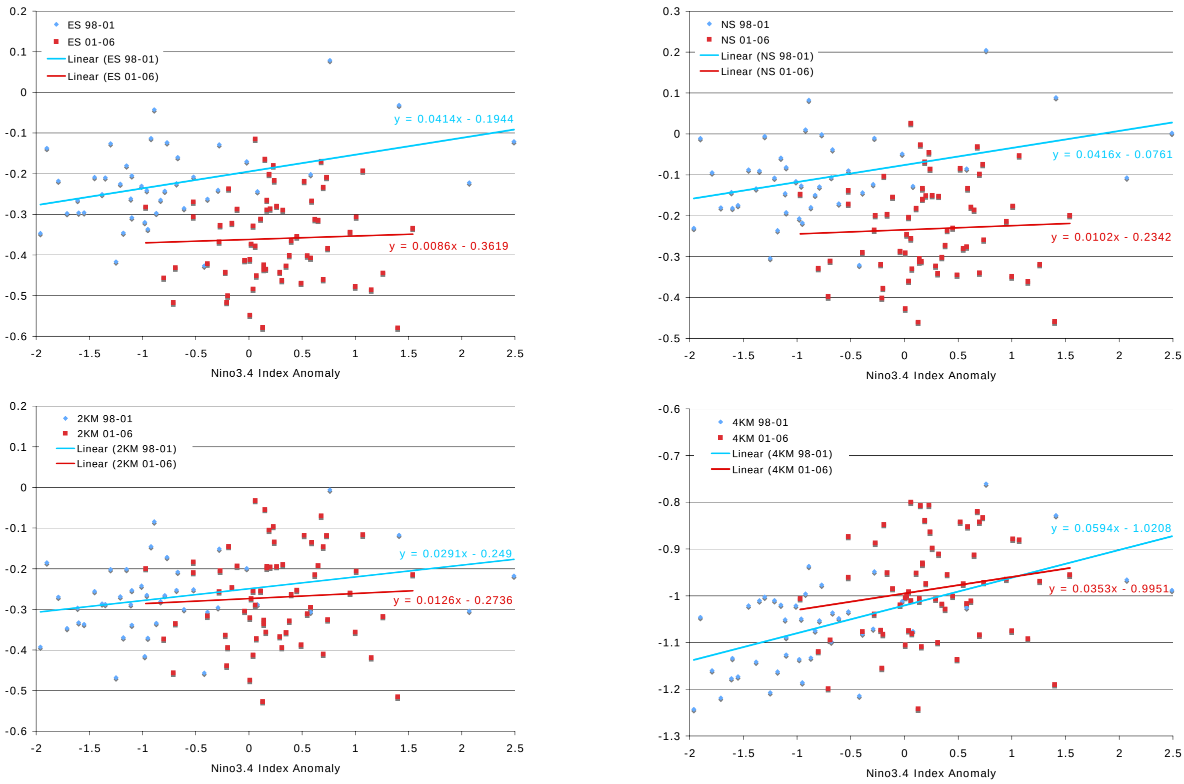


Fig.2 The PR rainfall anomalies (°/day) over the tropical ocean (25°S-25°N) versus Nino3.4 index at estimated surface, near surface, 2km, and 4km.

The PR monthly rainfall anomalies over the tropical ocean versus the Nino3.4 index anomalies for the pre-boost and post-boost periods are shown in Fig. 2. The linear regression line for the pre-boost period (1998-2001) has a relatively steep slope, while the linear regression line for the post-boost period (2001-2006) is nearly flat. The PR rainfall anomalies over the tropical ocean during the pre-boost period have a positive correlation with Nino3.4 anomalies, while the correlation between PR rainfall anomalies and Nino3.4 anomalies during the post-boost period is quite weak. Another interesting feature in Fig. 2 is that for the pre-boost period, Nino3.4 swings from large negative (La Nina) to large positive (El Nino) numbers. The pre-boost period went from a strong El Nino during the first few months of 1998 to a strong La Nina for most of the rest of the period up to August 2001. On the other hand, for the post-boost period, Nino3.4 has a small range centered on neutral conditions. This relatively small range may partially contribute to the lack of correlation between PR rainfall anomalies and Nino3.4 during the later period. Despite of the linear regression line with relative deep slope for the pre-boost period and the relative flat regression line for the post-boost period, our hypothesis is confirmed that the two linear regression lines have a significant gap with the rainfall anomalies for the post-boost period at a lower value compared to that for the pre-boost period. The results also seem to confirm that the ENSO phase should be taken into account. Fig. 2 also shows the significant gap between the linear regression lines for pre-boost and post-boost periods for the lowest levels (Figs. 2a and 2b) and a reduced gap at the 2 km level (Fig. 2c). The gap disappears at the 4km level (Fig. 2d) and above (not shown).

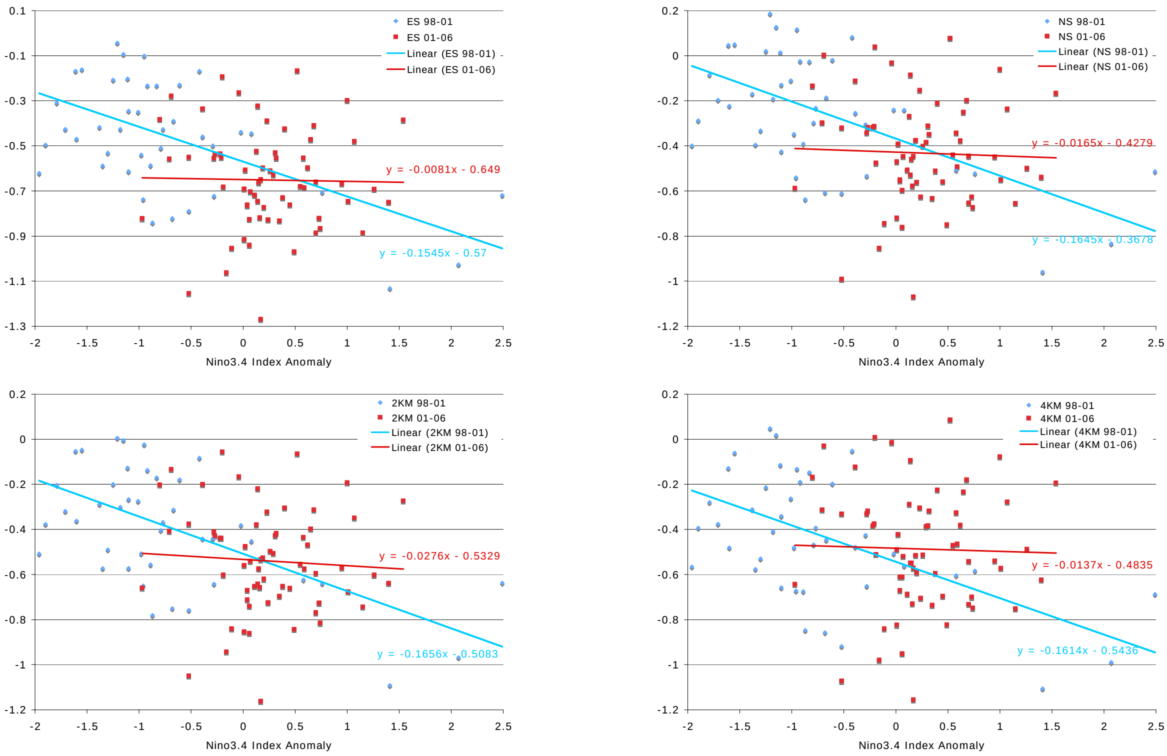


Fig.3 The PR rainfall anomalies (°/day) over the tropical land (25°S-25°N) versus Nino3.4 index at estimated surface, near surface, 2km, and 4km.

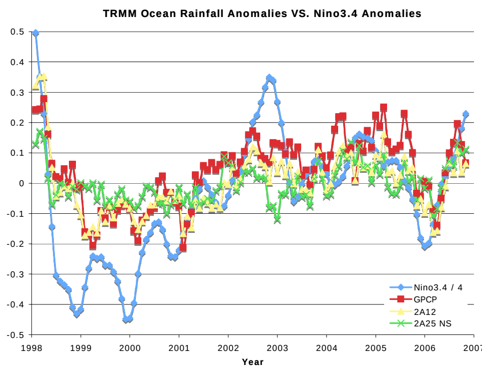
A similar analysis is also performed for the PR monthly rainfall data over the tropical land using GPCP rainfall data (Fig. 3) for the climatology. For the pre-boost period (1998-2001), which contains both strong La Nina events and strong El Nino events, the PR rainfall anomalies over the tropical land as expected show a clear negative correlation with Nino3.4 anomalies. However, for the post-boost period (2001-2006), which contains mostly near neutral years, the correlation between the PR rainfall anomalies and Nino3.4 anomalies is less significant. Different from the PR rainfall relations over tropical ocean shown in Fig. 2, the regression lines for the pre-boost period and post-boost period rainfall anomalies over tropical land cross each other in the middle of Fig. 3 (Nino3.4 index range of 0.5 to -0.5 from ES to 4-km level). In other words, compared to tropical ocean, the rainfall anomalies over tropical land have little statistical difference from pre-boost period to post-boost period at all of the analyzed levels from the ES to 4-km (Fig. 3). Therefore, no adjustment is made for PR rainfall during the post-boost period over tropical land. The possible causes to the difference over land and ocean are still under investigation by the PR algorithm developers.

Based on these results a procedure to adjust the mean PR-based, monthly rainfall over the tropical ocean for the post-boost period was determined. The differences between the monthly rainfall anomalies for the post-boost period (September 2001 to December 2006) indicated by the 64 red squares (Fig. 2) and the pre-boost period indicated by the blue linear regression lines (Fig. 2) are calculated. Corresponding to the same Nino3.4 index, the mean PR rainfall during the post-boost period is about 6.5%, 6.0%, 1.0% less than that of pre-boost period for the ES, NS, and 2km levels, respectively.

From the analyses shown in this section, the post-boost period PR rainfall is adjusted by adding 6.5%, 6.0%, and 1.0% to the monthly PR rainfall data over the ocean at ES, NS, and 2km level, respectively. No adjustment is made for data over land or above the 4 km level..

RELATIONS BETWEEN MONTHLY RAINFALL AND SURFACE TEMPERATURE

The relationships between variations of tropical rainfall and surface temperature can now be examined with the adjusted PR information and that from the TMI passive microwave instrument (for which no adjustment was needed). The positive correlation between SST and the rainfall measured by satellite passive microwave observations is well established (Soden 2000, Berg et al. 2002, Adler et al. 2003b). Our focus is to use the TRMM rainfall dataset, including the PR in comparison to the passive microwave data, to examine its response to surface temperature variation. Fig. 4a shows the time history of the ocean rainfall anomalies during the TRMM period, along with the Nino 3.4 index, to give a sense of the relation with ENSO. The ocean rainfall is positively correlated with the central Pacific Ocean ENSO index, although the correlation is less than if only the central Pacific Ocean rainfall would be used. Fig. 4b repeats the rainfall anomalies, but now shows the mean tropical ocean SST anomaly. There is general agreement between the mean SST and mean rainfall variations during the period, especially at longer time scales. The PR NS data show smaller amplitudes than that from the passive microwave observations.



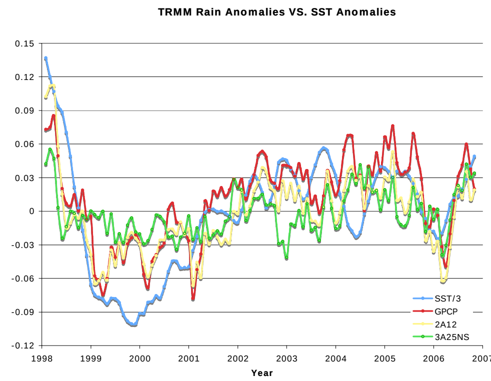


Fig.4 Times series of ocean rainfall anomalies (mm/d) from GPCP, TRMM TMI (2A12), TRMM PR (3A25 Near Surface), and a) Nino3.4 index anomalies (divided by 4), b) SST anomalies (divided by 3).

The variations of monthly rainfall measurements from TRMM (including TMI and PR at different levels) and GPCP against the variation of mean SST in the tropical region (25°S-25°N) are displayed in Fig. 5. As expected, tropical ocean rainfall is positively correlated with mean ocean SST (Fig. 5a). The comparison of the slopes among the TRMM TMI, TRMM PR (at different levels), and GPCP rainfall is listed in Table 2. Over the ocean, GPCP and TRMM TMI (2A12) rainfall data have large and similar slopes against SST anomalies (about 15%/°C). The good agreement between GPCP and TRMM TMI rainfall is not a surprise, because the major measuring instrument driving both datasets is a satellite microwave imager. However, the monthly rainfall anomalies derived from the TRMM PR (3A25) exhibit very different slopes against the SST anomalies at the different levels over the ocean. At lower levels, including ES, NS, and 2km level, the linear regression lines of monthly rainfall anomalies are relatively flat. The total rainfall amount from TRMM PR is significantly reduced from 2km to 4km, and further to 6km. But percentage wise, the monthly rainfall at 4km and 6km is more sensitive to SST, showing linear regression lines with larger slopes. One interpretation of this observation is that the rainfall resulting from the deep convection over the ocean is more controlled by the variation of SST.

The reason causing the different relationships of SST anomalies and the rainfall anomalies derived from microwave imager and precipitation radar is still unclear. One possibility is the difference between radiometer and radar in the physical principles for sensing rainfall. Radar measurements involve only the backscattering and attenuation of microwaves caused by the hydrometeor at a certain level. Radiometric measurements, however, correspond to an integration of the water liquid in the whole column of the atmosphere. The surface rainfall is estimated from this column of liquid water in the passive microwave estimation techniques. One can see from the figure that a vertical integration of the PR slopes at different altitudes might produce a slope comparable with that of the passive microwave. It is also possible that attenuation correction deficiencies may limit the lowest level of radar retrievals, especially for deep convective systems. In summary, the ocean surface temperature to ocean rain relationship established with passive microwave is not clearly supported by the TRMM PR data, unless the 4 km level PR data is shown to best represent surface rain variations.

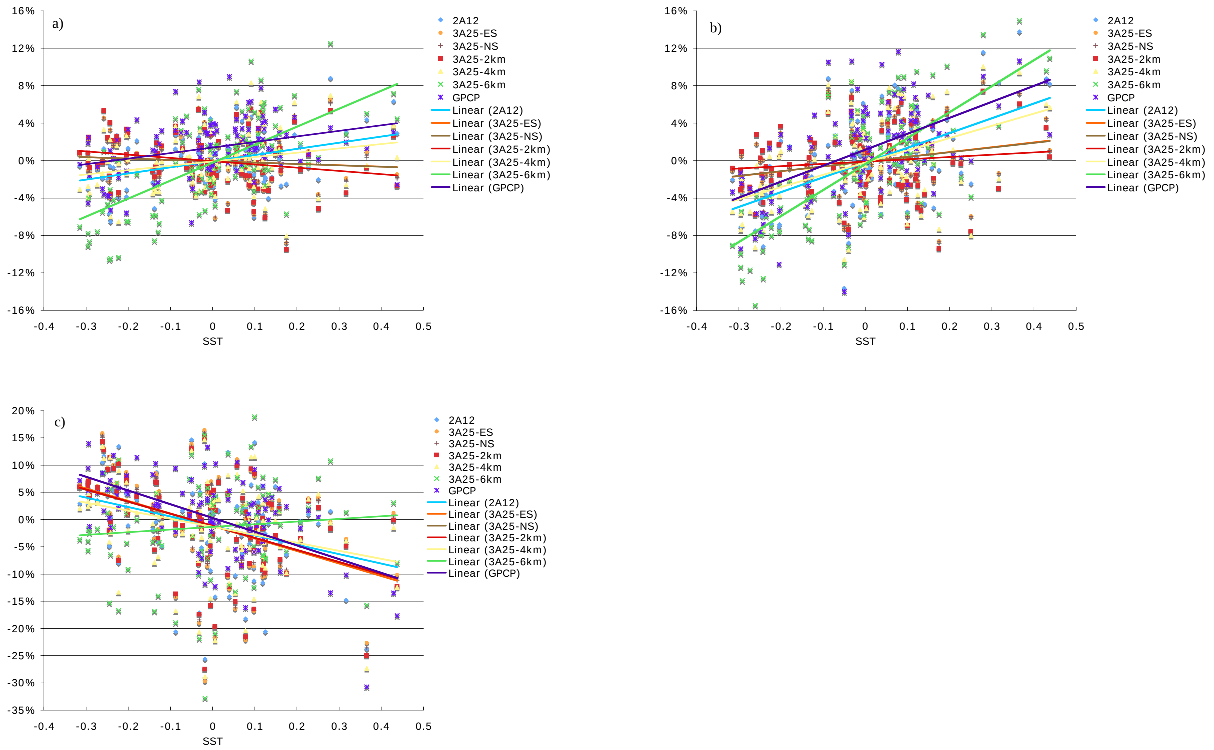


Fig.5 Percentage of monthly rainfall anomalies versus SST anomalies in a) total tropical region, b) tropical ocean, and c) tropical land.

Table 2 The slopes of the linear regression lines for TRMM TMI, TRMM PR and GPCP monthly rainfall anomalies to SST anomalies (%/°C)

	Ocean+Land	Ocean	Land
GPCP	5.9	16.7	-25.8
TRMM TMI	6.5	15.4	-16.9
TRMM PR Estimated Surface	-1.4	4.4	-16.9
TRMM PR Near Surface	-1.5	4.3	-16.7
TRMM PR 2 km	-3.5	1.7	-18.3
TRMM PR 4 km	4.6	11.9	-14.3
TRMM PR 6 km	19.2	26.6	4.8

The relation between land rainfall and ocean mean SST has a negative slope (Fig. 5b), except for PR at 6 km. The regression lines for TRMM TMI and TRMM PR rainfall below 4 km have a range of slope from -18.3%/°C to -14.3%/°C, while the regression line for GPCP rainfall shows a somewhat deeper slope at -25.8%/°C. The flat regression line for PR at 6 km may imply that, although the rainfall over land has a negative correlation with SST, the deep convection over land may have weaker connection to SST.

When the ocean and land rain is combined and the relation between total tropical rain and ocean SST is examined (Fig. 5c), the slopes are generally reduced due to the compensating effects of the land and ocean rain anomalies. However, a positive slope between ocean temperature and tropical rainfall still is present for the passive microwave observations (GPCP and TMI[2A12]) and for PR observations above 2 km. The magnitude of the slope (see Table 2) is about 6%/°C. This positive slope is in agreement with the conclusion from both GPCP data analysis by Gu et al. (2007) and modeling simulations by Su et al (2003). However, the PR-based slopes at altitudes 2 km and below are slightly negative, thereby failing to confirm even the sign of the relation. Again this might be related to attenuation problems with PR retrievals, or might be related to complicated vertical structure relations as discussed before.

SUMMARY AND CONCLUSIONS

Rainfall information from TRMM during the nine-year (1998-2006) period enables an independent look at some basic rainfall-temperature relations being derived from previous data set, e.g., GPCP. The TRMM data also allows for both radar and passive microwave observations to be used.

First, a technique is derived to account for the changes in the radar-based estimates caused by the increase in the TRMM satellite orbit from 350 to 402 km in August 2001. After that, the TRMM PR rainfall data shows an apparent drop during the post-boost period, especially at the lower levels. A simple and robust technique is developed to adjust the PR monthly rainfall data in Tropics (whole ocean and whole land) during the post-boost period, taking into account the impact of ENSO events. Based on the relationship between TRMM PR rainfall and Nino3.4 index, an indicator of ENSO events, before and after the boost of TRMM satellite, the post-boost period PR rainfall is adjusted by adding 6.5%, 6.0%, and 1.0% to the monthly PR rainfall data over the ocean at estimated surface, near surface, and 2km level, respectively. No adjustment is made for data over land or above the 4 km level.

The relationships between the tropical rainfall and surface temperature are then examined with both the TMI and adjusted PR data. Our focus is to use the TRMM rainfall dataset, including the PR in comparison to the passive microwave data, to examine its response to surface temperature variation. Over ocean-land combined, TRMM TMI (2A12) and GPCP rainfall data have rather similar small positive slopes (about 6%/°C), but PR (3A25) rainfall data slope is near zero except at 4km level. In other words, the surface temperature to rain relationship established with passive microwave is not supported by the TRMM PR data, unless the 4 km level PR data can be shown to best represent surface rain variations. The same results hold for ocean rainfall/mean SST relations. The reason causing the different relationships of surface temperature anomalies and the rainfall anomalies derived from microwave imager and precipitation radar is still unclear. It may be result of PR retrieval error, or inherent passive/active retrieval differences. Further research is needed to advance the use of TRMM data in this regard.

REFERENCES

Adler, R. F, and coauthors, 2003a: The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-present). *J. Hydrometeor.,* **4**, 1147-1167.

Adler, R.F., C. Kummerow, D. Bolvin, S. Curtis, C. Kidd, 2003b. Status of TRMM Monthly Estimates of Tropical Precipitation, in *Symposium on Cloud Systems, Hurricanes and TRMM, Meteorolgical Monographs,* **29(**51*),* edited by W.-K. Tao and R. Adler, 223-234.

Berg, W., C. Kummerow, and C. A. Morales, 2002: Differences between East and West Pacific Rainfall Systems. *J. Climate*, **15**, 3659–3672.

Chiu, L. S., and A. T. Chang, 2000: Oceanic rain column height derived from SSM/I. *J. Climate*, **13**, 4125–4136.

Curtis, S., and R. F. Adler, 2003. Evolution of El Niño-precipitation relationships from satellites and gauges. *JGR–Atmospheres*, **108**(D4), 4153, doi:10.1029/ 2002JD002690, 2003.

Gu, G., R. F. Adler, G. Huffman, and S. Curtis, 2007: Tropical rainfall variability on interannual-to-interdecadal/longer-time scales derived from the GPCP monthly product. *J. Climate*, **20**, 4033-4046.

Kwiatkowski, J., Y. Ji, and J. Stout, 2007: TRMM analysis toward algorithm improvement. *NASA Precipitation Measurement Missions (PMM) science team meeting*. Atlanta, GA.

Kummerow, C. and Coauthors, 2000: The status of the tropical rainfall measuring mission (TRMM) after two years in orbit. *J. App. Meteor.*, **39**, 1965-1982.

Kummerow, C. and Coauthors, 2001: The Evolution of the Goddard Profiling Algorithm (GPROF) for Rainfall Estimation from Passive Microwave Sensors. *J. App. Meteor.*, **40**, 1801-1820.

Robertson, F. R., D. E. Fitzjarrald, and H.I. Lu, 2007: Recent water and energy cycle variations as seen from TRMM and other sensors. *NASA Precipitation Measurement Missions (PMM) science team meeting*. Atlanta, GA.

Simpson, J. (Ed.), 1988: TRMM: *A Satellite Mission to Measure Tropical Rainfall, Report of the Science Steering Group.* National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland 20771, 94pp.

Soden, B. J., 2000: The sensitivity of the tropical hydrological cycle to ENSO. *J. Climate,* **13**, 538-549.

Su, H., D. Neelin, and J. E. Meyerson, 2003: Sensitivity of tropical tropospheric temperature to sea surface temperature forcing. *J. Climate,* **16**, 1283-1301.

Takahashi, N., T. Iguchi, 2004: Estimation and correction of beam mismatch of the precipitation radar after an orbit boost of the Tropical Rainfall Measuring Mission satellite, IEEE Trans., Geo. and Remote Sense., **42**, 2362-2369.

Wentz, F. J., L. Ricciardulli, K. Hilburn, and C. Mears, 2007: How much more rain will global warming bring? *Science*, **317**, 233-235.