Direct Validation of TRMM/PR Near Surface Rain over the Northeastern Indian Subcontinent Using a Tipping Bucket Raingauge Network

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Abstract

The near surface rain (NSR) dataset of the Tropical Rainfall Measurement Mission (TRMM) Precipitation Radar (PR) 2A25 V7 was validated using 36 tipping bucket raingauges installed over the northeastern Indian subcontinent, which correspond with the rain center of the Asian summer monsoon. This raingauge network covers the Brahmaputra flood plains and mountainous areas, including the Meghalaya Plateau, which is one of the wettest places in the world. We analyzed data from 2004 to 2013, and obtained 28,207 TRMM/PR-raingauge matchups with 2,170 TRMM/PR rainy field of views. Using them, we detected a reasonable time lag of around 300 seconds between the estimates from the TRMM/PR NSR and raingauges. Significant and large underestimations of TRMM/PR NSR were detected during the monsoon season (June–September) over the large areas of Meghalaya, Sylhet, and Barak. The bias ratios were −51.3% and −35.2% for the Meghalaya and Sylhet-Barak areas, respectively. In the Meghalaya subregion, major contribution to underestimation came from moderate TRMM/PR NSR from stratiform systems, and missed detection error was secondary contributor. In Sylhet-Barak subregion, moderate TRMM/PR NSR from convective systems largely contributed. Underestimation was not detected in premonsoon season (March–May).

(Citation: Terao, T., F. Murata, Y. Yamane, M. Kiguchi, A. Fukushima, M. Tanoue, S. Ahmed, S. A. Choudhury, H. J. Syiemlih, L. Cajee, A. K. Bhagabati, P. Bhattacharya, S. Dutta, R. Mahanta, and T. Hayashi, 2017: Direct validation of TRMM/PR near surface rain over the northeastern Indian subcontinent using a tipping bucket raingauge network. SOLA, 13, 157–162, doi: 10.2151/sola.2017-029.)

1. Introduction

In 1997, the Tropical Rainfall Measurement Mission (TRMM) satellite was launched (Kummerow et al. 1998; Iguchi et al. 2000, 2009). The observation was completed on 1 April 2015. The first spaceborne precipitation radar (PR) on this satellite accumulated a large amount of rainfall intensity estimations for these 17 years within 35 degrees north and south of the equator. The extended life time of the mission enabled us to research climatological spatial and temporal rainfall pattern with high spacial resolution using TRMM/PR data (Bhatt and Nakamura 2005; Hirose and Nakamura 2005).

Rain gauges are the most reliable rainfall measurement instruments. However, as was discussed in Amitai et al. (2012), lack of availability of direct matchups data, and difference in temporal and spatial scales between TRMM/PR sensor and raingauge, were responsible for reduced direct comparison studies. Previously, studies were focused on accumulation of rainfall amount, which identified averaged scores of TRMM/PR measurements (e.g., Adeyewa and Nakamura 2003). However, as was discussed in Wolff and Fisher (2008), to estimate detailed statistical structures of TRMM/PR sampling or the probability distribution of rainfall intensities that is critical to the analysis of extreme events, we have to clarify the statistical characteristics of direct and instantaneous matchups of TRMM/PR near surface rain (NSR) against raingauges. Such a comparison is crucial for the improvement of rain profiling algorithms for spaceborne radar sensors.

Bowman (2005) attempted direct matchup of TRMM/PR and the raingauges on TAO/TRITON buoy array over the tropical Pacific ocean, although 1 × 1° areas, not the TRMM/PR sensor resolution scale, was focused on. One of the most successful direct comparison was made in Amitai et al. (2012). They compared the instantaneous TRMM/PR NSR with a very dense weighing raingauge network with 1-min reporting time in the Walnut Gulch Experimental Watershed in Arizona, USA from 1999 to 2010. However, their comparison was limited to a specific well controlled field. Same method cannot easily apply to other areas. Seto et al. (2013) analyzed the quality of TRMM/PR NSR using 1-minute and 10-minute raingauge datasets over Japan. But they did not proceed to the comparison among different season and topographic features. Prat and Barros (2010) investigated the orographic effect on the TRMM/PR NSR accuracy using raingauges, identifying large underestimation in TRMM/PR NSR over the complex terrain in the Southern Appalachian mountains. They further noted that the underestimation reached −59% for the tropical storm case.
Thus, more direct and instantaneous validation by raingauges and other instruments over the areas with diverse climate and topographic conditions must be performed. In this regard, torrential rainfall, orographic effect, distinct seasonality, and complex topography of the northeastern Indian subcontinent make it a good field in which the TRMM NSR can be validated. This is one of the heaviest inland rainfall-receiving areas in the world (Murata et al. 2008; Kiguchi and Oki 2010). They have distinct premonsoon rainfall with severe local storms, before the onset of summer monsoon (Weston 1972; Yamane et al. 2010; Mahanta et al. 2013; Stiller-Reeve et al. 2015). Shige and Kummerow (2016) pointed out that heavy orographic rainfall over coastal mountain ranges of the Asian monsoon was associated with low precipitation-top heights. This may also be another factor that should be considered for the TRMM/PR rainfall retrieval over this region. Over the northeastern Indian subcontinent, TRMM/PR rainfall estimates have been utilized in the analysis of high spatial resolution rainfall distribution (Bhatt and Nakamura 2005; Bookhagen and Burbank 2006; Romatschke and Houze 2011). However, no direct instantaneous validations have ever been conducted over this area.

Over this region, we constructed a raingauge network from 2004, and have maintained them to the present day (Table S1). A number of TRMM/PR-raingauge matchups comparable to or larger than those from earlier studies are expected. In the present study, we will confirm the availability of this unique raingauge network for the direct instantaneous validation of TRMM/PR NSR. The major purpose of the present study is to determine the accuracy of TRMM/PR NSR estimates in different seasons, regions, rainfall intensity ranges, and rainfall types through a direct validation with this unique raingauge network over the northeastern Indian subcontinent.

2. Data and Methods

We utilized the data obtained from 2004 to 2013 from 36 raingauges (Figs. 1b and 1c), although the period of analysis varied from raingauge to raingauge (Table S1). We set up raingauges with a 0.5 mm resolution manufactured by Ikeda Keiki Company and Dynalab Weathertech in almost all the stations in Bangladesh and India, respectively. For the data logger, we utilized the HOBO Pendant Event Logger, UA-003-64 by the Onset Computer Corporation, and India, respectively. For the data logger, we utilized the HOBO gauges with a 0.5 mm resolution manufactured by Ikeda Keiki Company and India, respectively. For the data logger, we utilized the HOBO gauges with a 0.5 mm resolution manufactured by Ikeda Keiki Company and India, respectively. For the data logger, we utilized the HOBO gauges with a 0.5 mm resolution manufactured by Ikeda Keiki Company and India, respectively. For the data logger, we utilized the HOBO gauges with a 0.5 mm resolution manufactured by Ikeda Keiki Company and India, respectively. For the data logger, we utilized the HOBO gauges with a 0.5 mm resolution manufactured by Ikeda Keiki Company and India, respectively. For the data logger, we utilized the HOBO gauges with a 0.5 mm resolution manufactured by Ikeda Keiki Company and India, respectively. This test was performed only when more than 20 non-zero samples were available. Simple average of samples were expressed by an overbar ‘’.

Here we define a bias ratio \( r \) and a partial bias ratio \( \rho \). Consider a set of error estimates \( E_i = [\Delta R_i] \), \( i = 1, 2, \ldots, N \). The bias ratio of the set \( E \) is defined as:

\[
r = \frac{\Delta R}{\Delta R} = \frac{\sum_{i=1}^{N} \Delta R_i}{N}.
\]

We partition the set \( E \) into \( n \) subsets \( F_i \), \( i = 1, 2, \ldots, n \) according with any criteria. Using them, we can define the partial bias ratio \( \rho_i \) for \( F_i \) as:

\[
\rho_i = \frac{\sum_{i=1}^{N} \Delta R_i}{N}.
\]

Since \( r \) and \( \rho_i \) satisfy

\[
r = \sum_{i=1}^{n} \rho_i \rho_i/\rho_i \text{,}
\]

we may call \( \rho_i \) as a contribution to \( r \).

Some of analysis were conducted for premonsoon and monsoon seasons separately. In the present study, we defined premonsoon and monsoon seasons as March–May and June–September, respectively (Mahanta et al. 2013; Sarker et al. 2016).

3. Detection of time lag of the raingauge data

To increase the advantage of the direct validation of TRMM/PR NSR, we detected the time lag \( \tau \) between \( R_t \) and \( R_g \). We calculated correlation coefficients between \( R_t \) and \( R_g \) for pairs of 100, 200, \ldots, 500 highest \( R_t \) cases (Fig. 2a). We selected \( D = 3.5 \text{ km} \), so that all raingauges could match up with at least one nearest ray whenever the swath passed over. We set \( \Delta t \) as 150 seconds. The reason will be explained later. The time lag \( \tau \) was tested from \( -36,000 \) to \( 36,000 \text{ seconds at every 60 second interval, though only seconds from -900 to 1,200 were shown in Fig. 2a. Because the correlation coefficient was the largest at around 300 or 360 seconds, we set the time lag \( \tau \) at 300 seconds, i.e. 5 minutes. Averaged difference between raingauge altitudes and corresponding CFB heights was 1,559 m (1,311 m for Meghalaya subregion, and 1,251 m for other), and calculated velocity of raindrops was almost 4 m s\(^{-1}\), being consistent with Niu et al (2010). This was similar to those of Amitai et al. (2012) and Seto et al. (2013).
We confirmed the robustness and representativeness of parameters $\tau = 300$ seconds, $D = 3.5$ km, and $D_t = 150$ seconds. The same statistics as Fig. 2a except for randomly selected half samples were shown in Fig. 2b. For most of the half samples, maximum correlation coefficients appeared at $\tau = 300$ or 360, confirming the robustness of the peak in Fig. 2a. Figure 2c is the same as Fig. 2a except for $D = 2.5$ km. The maximum correlation coefficients for $D = 2.5$ km were seen at around 360 seconds, slightly longer than Fig. 2a. Correlation coefficients were smaller than those for $D = 3.5$ km, indicating robustness and advantage of $D = 3.5$ km. Figure 2d shows correlation coefficient patterns for three different $D_t$, 30, 150, and 300 seconds. Values of $\Delta t = 30$ and 300 seconds correspond to the cases in Seto et al. (2013). For $\Delta t = 30$ seconds, correlation coefficient was too changeable for small change of $\tau$. For $\Delta t = 300$ seconds case, the peak became smaller and broad compared with $\Delta t = 150$ second case. Therefore, we selected $\Delta t = 150$ second in the present paper.

We thus detected a reasonable time lag between the TRMM/PR NSR and raingauges based on long accumulated raingauge dataset. We obtained 28,207 valid TRMM/PR-raingauge matches with 2,170 TRMM/PR rainy views, by which we can develop reliable validation of TRMM/PR. Hereafter, we will show results for $\tau = 360$ seconds, $D = 3.5$ km, and $\Delta t = 150$ seconds. Nevertheless, we will discuss on results that are commonly observed for $\tau = 360$ seconds and/or $D = 2.5$ km cases.

4. Direct validation of TRMM/PR NSR

In Figs. 3a and 3c, scattered diagrams were shown for raingauge estimations $R_g$ and TRMM/PR NSR $R_t$ for all matchups for premonsoon and monsoon seasons. Because of the tipping count time window $\Delta t = 150$ seconds and the 0.5 mm resolution of the raingauge, values of $R_g$ were multiples of 6 mm h$^{-1}$. Figures. 3b and 3d aggregates corresponding scattered diagrams using partial bias ratios for logarithmically subdivided $R_t$ ranges.
that cases for $R_t < 0.1 \text{ mm h}^{-1}$ are included in the lowest $R_t$ range smaller than 0.215 ($= 10^{-2}$) mm h$^{-1}$. In the monsoon season, underestimation dominates in the very weak rainfall intensity range ($R_t < 0.215$ mm h$^{-1}$), and the moderate rainfall intensity ranges $2.15 < R_t < 21.5$ mm h$^{-1}$, which are almost equivalent to $2.5 < R_g < 30$ mm h$^{-1}$ under consideration of the bias ratios $-40 < r < -20%$. On the other hand, in the premonsoon season, underestimation was not found, and clear and robust results are not seen. Instead of Figs. 3b and d, we could plot the same for the categorization based on $R_g$. However, we plotted only those based on $R_t$ as shown above. It was because the categorization based on $R_g$ created a peculiar sampling bias pattern due to the descretization of $R_g$ values, resulting in figures that were not straightforward.

To investigate the bias in $R_t$ for each location, we displayed $\Delta R_t$ and bootstrap confidence intervals for $\Delta R$ samples in Fig. 4. Circle sizes are proportional to the magnitudes of error $\Delta R$. In the premonsoon season (Fig. 4a), overestimation significant at the 95% confidence level was detected at only one point. For the monsoon season (Fig. 4b), 95% significant underestimations were found at 5 raingauges in the Meghalaya and Sylhet areas. In Meghalaya, Sylhet, and Barak, the sizes of circles were also large, indicating large underestimation. Significant overestimation was found only at one station in the Assam Brahmaputra basin and one station in the Bengal Plain northeast of Sylhet.

In Table 1, we summarize these results into four subregions defined by the colors of the circles in Fig. 1. For the premonsoon season, reliable significant results cannot be obtained. Remarkable difference was seen in the monsoon season. Underestimation was found for the Meghalaya and Sylhet-Barak subregions at 99% confidence level. Bias ratios were $-51.3\%$ and $-35.2\%$ for the Meghalaya and Sylhet-Barak subregions, respectively.

In Figs. 5a and 5b, we showed the partial bias ratio for different rainfall intensity ranges for Meghalaya and Sylhet-Barak subregions in the monsoon season. In both subregions, major contribution to the bias ratio (80.2% and 65.5% contributions for Meghalaya and Sylhet-Barak subregions, respectively) came from moderate TRMM/PR NSR ranges with $R_t < 10.0$ mm h$^{-1}$. Since the bias ratios for the range $4.64 < R_t < 10.0$ mm h$^{-1}$ are $-45.3\%$ and $-39.8\%$ for Meghalaya and Sylhet-Barak subregions, corresponding raingauge measured rainfall intensity ranges are $R_g < 14.5$ mm h$^{-1}$ and $R_g < 14.0$ mm h$^{-1}$, respectively. For the Meghalaya subregion, contributions from very weak $R_t$ cases below 0.215 mm h$^{-1}$ were secondarily prominent. These results were not consistent with the result of Kirstetter et al. (2013) that elucidated the overestimation for lighter (< 10 mm h$^{-1}$) rainfall intensity in TRMM/PR. The cause of underestimation in moderate to weak TRMM/PR NSR in the present study have to be addressed.

Results shown above were commonly observed for $\tau = 360$ seconds and/or $D = 2.5$ km cases (not shown).

5. Discussion

Based on Prat and Barros (2010), Wilson and Barros (2014) analyzed TRMM/PR NSR over the complex topography of the Appalachian Mountains, USA, to detect large underestimations in TRMM/PR due to seeder-feeder interactions associated with low level fog or shallow cloud systems. In the monsoon season, the southern slope of the Meghalaya Plateau is frequently covered by dense fog, as was shown in the climatological tables provided by the India Meteorological Department (India Meteorological Department, 2015). The seeder-feeder interaction can be another possible explanation for the underestimation in the Meghalaya and Sylhet-Barak subregions during the monsoon season. The absence of underestimation in the premonsoon season can be explained by

![Fig. 4. Detected biases for each site for (a) premonsoon and (b) monsoon seasons. Areas of circles indicate magnitudes of under-/overestimation $\Delta R$, where size of circles in the legend correspond with under-/overestimation of 0.25 mm h$^{-1}$. Statistically significant points at 80 or 95% confidence levels were shown by red and blue colored circles as indicated by legends. Yellow and light blue circles were under-/overestimated, respectively, although they were not significant.](image-url)
the lower humidity over the Bengal Plain during the premonsoon season (Sarker et al. 2016). Shige et al. (2013) suggested that an active coalescence process in the shallow cloud near the ground level causes underestimation in TRMM Microwave Imager (TMI) rain retrievals.

We plotted vertical profiles of TRMM/PR rainfall rate (Fig. 6). The regional difference of the lowest level of the profiles arose from the elevated topography over the Meghalaya Plateau, which is about 1,000 m on average for raingauges, as distinct from the clutter depth. Figure 6 showed downward enhancement of precipitation in the lower layer for the Meghalaya and Sylhet-Barak subregions in the monsoon season. Labels on horizontal axis indicate the category numbers of rain types defined in the TRMM 2A23 algorithm: −88 - “no rain”, 100 and 120 - “stratiform certain”, 130 and 152 - “maybe stratiform”, 200 and 210 - “convective certain”, 300 - “others”.

There are many possible error sources in the TRMM/PR rainfall retrieval, such as insufficient attenuation correction, non uniform beam filling (NUBF) effects, uncertainty in other physical assumptions including the drop size distribution, and misclassification of convective-stratiform systems (Iguchi 2009; Kirstetter et al. 2013; Duan et al. 2015). Duan et al. (2015) analyzed the structure of underestimation in TRMM/PR over the Appalachian mountains (Prat and Barros 2010), to find the importance of “probably stratiform” and “no rain” cases. Their results were common to our results for Meghalaya subregion, indicating that similar mechanisms may work in the underestimation over the Meghalaya plateau. Over the Sylhet-Barak subregion, separate from the Meghalaya subregion, the convective clouds played an important role in the underestimation. Such a difference may be relevant to the topography of the Sylhet-Barak subregion, which is a flat area just south of the Meghalaya Plateau. A deep cold pool above the Sylhet area, which was found in Kataoka and Satomura (2005) using a meso-scale model calculation, can be a remarkable feature that possibly affects the structure of convection in this area.

Thus, in the present study, we detected underestimations and contributions from different rainfall intensity ranges and rain types. However, we could not show direct evidence of the error source. Additional observations including the microphysical process just above the ground and analysis of vertical structure of reflectivity must be conducted in the near future.

6. Conclusions

Utilizing 36 tipping bucket raingauge datasets from 2004 to 2013, we conducted direct and instantaneous validation of the near surface rain (NSR) of TRMM/PR 2A25 V7 dataset over the northeastern Indian subcontinent, which is the heart of the Asian summer monsoon. We obtained 28,207 TRMM/PR-raingauge matchups with 2,170 TRMM/PR rainy FOVs. This sampling size of the validation was large enough to detect a reasonable time lag of around 300 seconds in the raingauge estimate behind TRMM/PR NSR.

Among these raingauge locations, significant and large underestimation of TRMM/PR NSR were detected over the Meghalaya and Sylhet-Barak subregions only in the monsoon season (June-September), which correspond with large monsoon rainfall areas. The bias ratios were −51.3% and −35.2% for the Meghalaya and Sylhet-Barak subregions, respectively. This underestimation was seen only in the monsoon season (June-September), and not in the premonsoon season (March to May). In the Meghalaya subregion, major contribution to this underestimation came from moderate TRMM/PR NSR from possibly stratiform systems. Missed detection error was a secondary contributor in the Meghalaya region. In the Sylhet-Barak subregion, moderate TRMM/PR NSR from convective systems largely contributed to the underestimation.
Acknowledgments

This study was partially supported by JSPS grants-in-aid for scientific research (11691151, 12740269, 12574020, 15651103, 17255002, 18256005, 21403005, 23241057, 23240122, and 26220202), the MEXT 21st Century COE Program of Kyoto University, “Elucidation of the Active Geosphere from Asia and Oceania to the World”, and the Japan-Bangladesh joint study project on floods by the Japanese International Cooperation Agency (JICA). It was also supported by the Japan EOS Promotion Program (JEPP), the MEXT, “Development of rainfall observation system in Southeast Asia”, the Precipitation Measurement Mission conducted by Earth Observation Research Center, Japan Aerospace Exploration Agency (JAXA/EORC), and KAKEN Promotion Fund 2017 of Kagawa University Research Promotion Program (KURPP). We want to thank the anonymous reviewers and editor for their valuable comments. We greatly appreciate all the people in Bangladesh and India who supported our observational activity in the northeastern Indian subcontinent. Finally, our activity in Bangladesh received tremendous support from the late Mr. Quamrul Alam in BMD. We would like to dedicate this paper to him and his family, with our tremendous gratitude.

Edited by: R. Misumi

Supplement

Table S1: List of all rain gauges used in the present paper.

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Manuscript received 21 January 2017, accepted 1 August 2017 
SOLA: https://www.jstage.jst.go.jp/browse/sola/