Impact of Misrepresentation of Freezing-Level Height by the TRMM Algorithm on Shallow Rain Statistics over India and Adjoining Oceans

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ABSTRACT

The estimation of freezing level-height (FLH) by the Tropical Rainfall Measuring Mission (TRMM) algorithm is evaluated, against several other data sources, over India and adjoining oceans. It is observed that the TRMM algorithm either underestimates or overestimates the FLH [relative to radiosonde- and ECMWF Interim Re-Analysis (ERA)-derived FLH] at latitudes > 20°N over India. The agreement between the FLHs obtained from ERA and radiosonde and the TRMM-derived brightband height suggests that usage of ERA-derived FLH may improve shallow rain statistics. The impact of misrepresentation of FLH by the TRMM algorithm on shallow rain statistics is assessed by using 13 yr of TRMM precipitation radar measurements. It is noted that the misidentification of FLH alone affects (mostly underestimates) the shallow rain occurrence and rain fraction by 3%–8% over the study region. The magnitude of underestimation is large over the southern slopes of the Himalaya, the northern plains, and in northwestern India. TRMM identifies most of the shallow rain (30%–50%) as cold rain in regions where the underestimation of FLH is high. This situation could introduce some error in the correction of reflectivity for attenuation and in the retrieval of latent heat profiles.

1. Introduction

Shallow rain plays an important role in regulating the moisture content of the lower atmosphere and in modulating the recycling time scales of organized tropical convection (Lau and Wu 2003). It is ubiquitous over much of the tropical oceans (Short and Nakamura 2000; Schumacher and Houze 2003; Lau and Wu 2003), and therefore detailed characterization, in terms of frequency, intensity, and areal coverage, of this type of precipitation is important for better understanding weather and climate. The passive remote sensing detection of shallow clouds on the basis of outgoing longwave radiation may not be as effective as it is for deep convection (Masunaga and Kummerow 2006). The active remote sensors from space, such as the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR), are unique in that they provide high-resolution 3D profiles of precipitation, facilitating precise identification of different types of precipitation. Earlier studies that employed TRMM PR measurements have shown that the shallow rain forms over a large area (~70% of the total rain area) and accounts for a considerable percentage of total rainfall (~30%) in the tropics (Short and Nakamura 2000; Schumacher and Houze 2003; Lau and Wu 2003; Masunaga et al. 2005; Kodama et al. 2009; Short et al. 2009).

The operational TRMM PR algorithm 2A23 (version 6; hereinafter we refer to the algorithm simply as TRMM) divides the rainfall into shallow and deep rainfall on the basis of whether or not the storm height (SH) exceeded the freezing-level height (FLH) (Awaka et al. 1998, 2009). It uses climatological surface temperature and a pre-defined lapse rate to estimate the FLH and to identify...
the shallow rain. The validity of this approach has been debated in some earlier studies (Yamamoto et al. 2006). It was argued that the above approach may not provide correct estimates of FLH at midlatitudes—in particular, during winter. Therefore, Yamamoto et al. estimated the FLH from vertical profiles of National Centers for Environmental Prediction temperature data interpolated in time and space to the satellite measurement location. In the present study, TRMM’s identification of FLH is evaluated over India by comparing it with those estimated independently from the European Centre for Medium-Range Weather Forecasts Interim Re-Analysis (hereinafter ERA) and radiosonde measurements at 33 stations across India. The impact of misrepresentation of the FLH by TRMM on shallow rain statistics is also assessed in this article. Further, implications of the misrepresentation of FLH on attenuation correction and latent heat retrieval are briefly discussed.

This paper is organized as follows. Section 2 describes the data used in this study. Problems associated with the identification of FLH and how these problems affect shallow rain statistics are discussed in section 3. The results are summarized in section 4.

2. Data

This study uses 13 yr (1998–2010) of TRMM measurements (version 6, both 2A23 and 2A25) over the domain of interest (5°–40°N, 60°–100°E), covering the Indian landmass and adjoining oceans. The 2A25 dataset provides rainfall rate and attenuation-corrected reflectivity $Z$ (dBZ) profiles (Iguchi et al. 2000). To extend the lifetime of the TRMM satellite, the height of the satellite was raised to 402.5 km in August of 2001. The effects due to the satellite height boost, nevertheless, are small and barely discernible (Liao and Meneghini 2009; Awaka et al. 2009; Short and Nakamura 2010), and therefore all of the data (before and after the boost) are handled in a similar fashion. TRMM PR has a beamwidth of 0.71° and a scan angle of ±17°, providing $Z$ profiles up to 20 km with a range resolution of 250 m. The reflectivity data at each range bin in each angle ray are referenced to the same coordinate pair at the earth’s ellipsoid, despite the angular offset (Houze et al. 2007). There is no offset at nadir, but it increases as the angle from nadir increases. At higher altitudes the most significant offset is observed. Therefore, only angle bins within 7° from the nadir (21 out of 49 fields of view) are considered in this study. At higher altitudes the most significant offset is observed. Therefore, only angle bins within 7° from nadir (21 out of 49 fields of view) are considered in this study. At higher altitudes (>15 km) and for a 17° scan angle, the estimated offset is ~5 km. Angle bins within 7° will have an offset of less than 2 km. The restriction of scan angle limits the swath width to ~86 (98) km, instead of 215 (245) km before (after) the boost. The other advantage of limiting the scan angle is that it minimizes the issues related to surface-clutter contamination in shallow rain (Short and Nakamura 2000). Following Short and Nakamura (2000), the SH is derived in this study by using reflectivity profiles within ±7° from the nadir. The SH is the maximum altitude below which the PR reflectivity is ≥17 dBZ for at least three immediate range bins (Short and Nakamura 2000; Radhakrishna et al. 2009). The original high-resolution data (~5 km in space) over the Indian region are gridded into 0.5° × 0.5° bins.

TRMM measurements are augmented with 13 yr of ERA data products (Dee et al. 2011) and radiosonde
measurements (available at 0000 and 1200 UT) at 33 stations spread across India (Fig. 1). Dee et al. (2011) elucidated the configuration and performance of the data assimilation system of the ERA data. It provides 1.5° × 1.5° gridded data, which later were interpolated to 0.5° × 0.5°.

3. Results and discussion

a. Problems associated with the misrepresentation of FLH

To identify shallow rain, the TRMM requires the FLH. Version 6 of 2A23 uses climatological temperature at sea level \( T_s \) (K) and assumes a lapse rate to compute the FLH in kilometers (Awaka et al. 2009):

\[
\text{FLH} = \left( T_s - 273.13 \right) / 6.0.
\]

The \( T_s \) data are static and consist of monthly averages, provided by the National Aeronautics and Space Administration before the launch of the TRMM satellite, and they have not been updated (Awaka et al. 2009). We, therefore, assessed the validity of the TRMM-estimated monthly mean FLH by comparing it with monthly mean FLHs obtained from radiosonde measurements and ERA at radiosonde stations (interpolated to the radiosonde station location). The height of the bright band, which is one of the richest sources for obtaining FLH data during stratiform rain, obtained from the PR is also employed in this study.

Figure 2 shows typical comparison plots of monthly means of FLH estimated from radiosonde, ERA, and TRMM data. It also shows PR-derived monthly mean brightband heights, averaged over 0.5° × 0.5° centered on radiosonde locations. It is clearly evident from Fig. 2 that the annual variation of monthly mean FLH is latitude dependent (Harris et al. 2000; Thurai et al. 2005). The month-to-month variability of FLH is smaller over the low-latitude stations, both land and island (<20° latitude—stations numbered 19, 20, 22, 23, 24, 25, 26, 27, 28, 29, 31, 32, and 33 in Fig. 1). For instance, in Figs. 2e and 2f, the month-to-month variability of FLH at Mangalore and Cochin, respectively, is less than 200 m. 

FIG. 2. Comparison of monthly mean FLHs obtained from radiosondes, ERA, and TRMM. The error bar denotes the standard deviation. The latitude and longitude of the corresponding station are also shown. The overlaid symbol (with error bar) is the monthly mean (std dev) brightband height, estimated from TRMM PR measurements, over the station.
All three estimates of FLH (i.e., by the radiosonde, ERA, and TRMM) are nearly equal, and their annual variation is also similar. As expected, the mean brightband height is found to be nearly 300–500 m below the mean FLH (Fabry and Zawadzki 1995).

At stations located at greater than 20° (covering northern India—stations numbered 1, 2, 3, 4, 7, 8, 10, 12, 13, 14, 16, and 17 in Fig. 1), TRMM underestimates the FLHs during the summer monsoon (June–September), the main rainy season. Figures 2a–d, which are for representative stations for that region, clearly show that the underestimation of FLH by TRMM can be as large as 1.1 km relative to radiosonde- and ERA-derived FLHs. Over these stations, the mean brightband height is surprisingly found above the TRMM-derived mean FLH, which is unrealistic. On the other hand, the FLHs that are derived from the radiosonde and ERA datasets are nearly equal and also their mean FLH is found to be above the brightband height, as expected from the microphysics point of view, giving full credence to the FLHs obtained from the radiosonde and ERA datasets.

At some stations (numbered 4, 13, and 14 in Fig. 1), TRMM overestimates the FLHs during the winter (December–February; Fig. 2a), as was also noted by Yamamoto et al. (2006). This also lends support to the argument that there is some problem in the estimation of FLH by TRMM, at least for latitudes of greater than 20°N.

To investigate the spatial extent of the misrepresentation of FLH and its relationship with latitude, spatial plots of FLH differences between TRMM and ERA (ERA FLH – TRMM FLH) for January and July are generated (Fig. 3). It is clear that TRMM underestimates the FLH by as much as 1 km during July along the southern slopes of the Himalaya, the northern plains, and in northwestern India. As noted in Fig. 2, in some regions (northwestern India during January and the equatorial region during July), TRMM overestimates the FLH, albeit with smaller magnitude (0.25 km). In general, at lower latitudes (<20°N), the under-/overestimation of FLH by TRMM is small (not statistically significant).

Note that the analysis presented here is based on version 6 of the 2A23 algorithm, which was recently replaced by version 7. Version 7 has two products (a standard product and a real-time product). The FLH is computed using Global Analysis data (GANAL) from the Japan Meteorological Agency in the standard product, and the FLH is estimated from climatological surface temperature data and a lapse rate of 6° km−1 (same as in version 6) for the real-time product. Since the standard product uses GANAL data, the bias in shallow rain statistics due to the misrepresentation of FLH could be small. Nevertheless, a detailed analysis needs to be made to ensure that the shallow rain statistics are correct. The real-time product, which is extremely useful for real-time applications and weather forecasting, still follows the old (version 6) approach, however. The shallow rain statistics that are based on this dataset, if any, also get biased by as much as 8%. Since the ERA-derived FLH provides better results on shallow rain statistics than does the FLH obtained from climatological surface temperature and a predefined lapse rate, we argue that it is better to use climatological ERA data even for the real-time product in version 7. Further, several interesting papers have appeared on shallow rain statistics based on older versions of the algorithm (Short and Nakamura 2000; Schumacher and Houze 2003; Lau and Wu 2003; Masunaga et al. 2005; Kodama et al. 2009; Short et al. 2009). The study that is
presented here clearly shows that those statistics might have been biased (by 3%–8%) because of the bias in FLH.

It is clear from Figs. 2 and 3 that there are problems in TRMM in estimating the FLH. We now discuss how they affect the shallow rain identification and its occurrence and rain-fraction statistics.

b. Implication of misrepresentation of the FLH on shallow rain statistics

Figure 4 provides a demonstration, using two examples, of how the misrepresentation of FLH affects the shallow rain. We also quantify the under- or over-estimation of shallow rain by TRMM. Figures 4a,b and 4c,d show the spatial distributions of shallow and deep rain, identified from the FLH as estimated by TRMM and ERA (used in this study), over the Himalayan region at 1720 and 2216 UT, respectively, on 19 July 2010. The rain is treated as shallow if the SH is below the height of FLH − 1 km. Both TRMM and this study correctly identify that most of the rain in both cases is associated with the deep clouds. It is, however, clearly apparent from Fig. 4 that the occurrence of shallow rain is more widespread when the FLH is taken from ERA. The percentage of occurrence of shallow rain is estimated as 6.7% and 23.6% (6.6% and 16.9%) by TRMM and this study, respectively, in the first (second) example. Since the same procedure is adopted in identifying the shallow rain by both the methods, the observed 10%–15% difference in the occurrence of shallow rain between TRMM and this study is arising as a result of the difference in the estimated FLHs by both of the methods.

To quantify the impact of misrepresentation of FLH on shallow rain statistics, we segregated the shallow rain from the total data using the FLH as given by TRMM and ERA. The same criterion is used in identifying the shallow rain; that is, rain is considered to be shallow if the SH is lower than the FLH by at least 1 km. The occurrence percentage and rain fraction of shallow rain obtained by both algorithms are shown in Fig. 5. Figure 5

\[ 19-07-2010, 17:20 - 17:22 \text{ UT} \]

\[ 19-07-2010, 22:16 - 22:17 \text{ UT} \]
also shows the differences in the shallow rain’s occurrence and rain fraction by both methods (Figs. 5e,f). TRMM underestimates (in comparison with this study) both the shallow rain occurrence and fraction by 3%–8% over the Indian region. The magnitude of the underestimation is large for the southern slopes of the Himalaya, the northern plains, and northwestern India, where the FLH computed by TRMM is found to be lower than that obtained by this study (see Figs. 2 and 3). Although the underestimated shallow rain constitutes only a small fraction of total rain, the problem still needs to be addressed for improving statistics of different types of rain. Underestimation of the shallow rain over the land by TRMM is also known from earlier studies (Kodama et al. 2009 and references therein). It means that the shallow rain occurrence (and also rain fraction) could be more than the values available in the literature (at least over India). Further, TRMM overestimates (relative to this study) the shallow rain occurrence by 2% in some regions (e.g., in latitudes of <10°N), where the TRMM-derived FLH is above the ERA-derived FLH. Since the same criterion is followed without changing any parameters except FLH, the observed differences in shallow rain statistics can be attributed to the misrepresentation of FLH by TRMM.

It is now clear from the above discussion that TRMM underestimates (overestimates in some regions) the shallow rain because of the misrepresentation of FLH in northern India. The obvious question is, What percentage of the shallow rain, as identified by the algorithm used in this paper (i.e., FLHs taken from ERA data), is being treated as cold rain by TRMM? To study the above aspect, we separated our algorithm’s shallow rain into TRMM’s shallow and cold rain based on our
SH and TRMM FLH. This ensures that the cold rain (and its statistics) identified from the above procedure are entirely due to the misrepresentation of FLH by TRMM. Figure 6 shows spatial maps for the percentage occurrence and rain fraction of TRMM PR–identified (following the above procedure) shallow and cold rain from our algorithm’s shallow rain category. It is clear from Fig. 6 that the TRMM classifies 30%–50% of the shallow rain from our algorithm as cold rain. The percentage occurrence and rain fraction of this category are large over the Indian landmass, particularly in regions north of 20°N.

In addition to biasing the shallow rain statistics, misrepresentation of FLH and identification of a considerable fraction of shallow rain as cold rain has several other implications in the retrieval of latent heating profiles and in correcting the reflectivity profile for attenuation. Many of the latent heat retrieval algorithms depend on SH, rain type, FLH, and the vertical profile of reflectivity (Tao et al. 2006). Depending on how a latent heating algorithm is implemented, the change in FLH could cause small differences in the estimated heating rates near the freezing level. Further, the coefficient $\alpha_o$ of the specific attenuation and $Z$ relation depends on the phase state of the hydrometeor and temperature, and therefore $\alpha_o$ is given as a function of altitude relative to the FLH (Iguchi et al. 2009). Therefore, any error in the FLH introduces some bias in the attenuation-corrected reflectivity. This error may not be significant in the stratiform rain, because the FLH information is directly obtained from the height of the bright band during stratiform rain.

**Fig. 6.** The spatial variation of (top) percentage occurrence and (bottom) rain fraction for (a),(c) shallow and (b),(d) cold rain as identified by TRMM from our algorithm’s shallow rain data.
4. Summary and conclusions

Thirteen years of TRMM PR measurements have been used to study the issues associated with the identification of the FLH and shallow rain statistics. This study puts its emphasis on the following question: What are the error statistics in the percentage occurrence and rain fraction estimations of shallow rain by TRMM in comparison with this study?

The validity of the PR-estimated FLH is assessed with independent datasets (ERA and radiosonde data). Agreement is found to be good at low-latitude stations (<20°N), but at other stations the FLHs obtained by TRMM PR are either higher (in the northernmost parts of India during winter) or lower (for the southern slopes of the Himalaya, the plains, and northwestern India during the summer monsoon) than other estimates. The impact of the under-/overestimation of the FLH by the TRMM on shallow rain statistics is found to be considerable (3%–8%) over the Indian landmass. The magnitude of underestimation of shallow rain is large over the southern slopes of the Himalaya, the plains, and northwestern India, where the TRMM FLH is found to be lower than the actual FLH (as obtained by radiosonde or ERA). TRMM PR identifies a considerable fraction of the shallow rain (30%–50%) as cold rain over the land.

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