Biases in the standard rain rate product by the TRMM microwave radiometer over land

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***Abstract*— This study investigates the causes of biases in the rain rate estimates by the TMI standard algorithm. Retrieval error is separated from rain/no-rain classification error. As it is well known, the retrieval error is sensitive to storm height. It is interesting that the observed brightness temperature at 85GHz shows clear diurnal variation for given storm height and surface rain rate. It can be explained by the diurnal variation of the land surface brightness temperature (related with the land surface physical temperature) under inhomogeneous rainfall or the diurnal variation of the freezing height (related with the air temperature).**

Keywords-TRMM; TMI; storm height; diurnal variation

I. Introduction

Rain rate estimates by TRMM Microwave Imager (TMI) can be quantitatively validated by comparing with the estimates by Precipitation Radar (PR) which is on the same platform. The observation and rain rate estimation technique of PR are completely different from those of TMI. Over land, it is widely acknowledged that the estimates by PR (denoted as *R_PR*) is much more reliable than the estimates by TMI (denoted as *R_TMI*). In this study, the rain rate estimates by PR using the standard algorithm version 6 is assumed to be perfect, then the error of the rain rate estimates by TMI using the standard algorithm version 6 can be calculated by $\Delta R=R\_TMI-R\_PR$. The purpose of this study is to statistically analyze ΔR and to examine causes of the error.

II. Data

A. The TMI Standard Algorithm

While there are many precipitation retrieval algorithms for TMI, this study goes with the latest version of TMI standard algorithm, which is developed by Kummerow et al [1]. This algorithm, one of the Goddard profiling algorithm (GPROF), applies statistical technique to retrieve rain rate. Below, we briefly introduce the land part of this algorithm. It consists of two steps: rain/no-rain classification (RNC, in short) and retrieval. RNC judges whether a TMI pixel has the rainfall signature (rain) or not (no-rain). Retrieval is done only for the "rain" pixels and is not applied for "no-rain" pixels, whose *R_TMI* becomes zero.

Characteristic precipitation profiles simulated by cloud resolving models with the calculated brightness temperatures are summarized as database. Retrieval process referred the databases to find the profiles to have brightness temperatures similar to the observed brightness temperatures. Over land, only one channel 85GHz Vertical (85V) is used, because lower frequency channels generally do not have much valid information of the precipitation. Two databases, one for convective precipitation and another for stratiform precipitation, are referred to give the estimates *R_TMI_C* and *R_TMI_S*, respectively. To merge the two estimates, CSI (Convective / Stratiform ratio Index) is calculated as explained below. Like as over-ocean algorithm, polarization method and texture method are used to judge convective or stratiform. CSI is calculated by the next equation (1).

$$\begin{aligned}CSI=&0.062+0.00887*\{1.11*TB(10V)-1.24*TB(37V)\\&+0.45*TB(85V)-1.25*(POL)+0.22*(NPOL)+1.24*(STDEV)\\&+0.14*(PIWD)-84.3\}\end{aligned} \quad (1)$$

POL and NPOL are indices used in the polarization method and STDEV and PIWD are indices used in the texture method. Among other terms, TB(37V) and TB(85V) have some information to be related with the precipitation, however, TB(10V) is generally not related with precipitation over land. The indices and channels are selected to statistically match CSI with the classification by PR efficiently. The reason why TB(10V) is selected is explained as "convection occurs more over warmed surfaces" in McCollum and Ferraro [2]. The final estimates *R_TMI* are calculated by equation (2)

$$R\_TMI=(1-CSI)*R\_TMI\_S+CSI*R\_TMI\_C \quad (2)$$

If CSI is unavailable, the third (mixed) database is referred to get the rain rate estimates *R_TMI_M*, then *R_TMI_M* is treated as the final estimates *R_TMI*. This database has both stratiform and convective precipitation profiles.

This study will examine not only apparent but potential characteristic of the rain rate estimates by the standard algorithm. For that, the standard algorithm with two minor modification (A) and (B) as below are applied for three years, January 1998 to December 2000.

(A) *R_TMI* is always derived over land even if the RNC is "no-rain".

(B) *R_TMI_M* is always calculated with *R_TMI*.

B. Match up with PR Data

As R_PR, near surface rain rate derived by the latest version of PR standard algorithm [3] is used. PR can not observe several ranges near surface because of the ground clutter, however, in version 6, Z profiles are extrapolated and rain rate are estimated at the surface level (stored as "e_SurfRain" in the product 2A25). Convective / Stratiform classification and the storm height (SH) derived by the PR standard algorithm are also used for the analysis.

Single or multiple (usually two) PR pixels within a TMI footprint for 85GHz (7.2km along track x 4.6km cross track) are matched up with the TMI pixel. As a result, following variables become available for each TMI pixel.

- RNC by TMI; T (rain) or t (no-rain)
- R_TMI (rain rate estimates by TMI using convective and stratiform databases); according to (A), R_TMI is always calculated
- R_TMI_M (rain rate estimates by TMI using mixed database); according to (B), R_TMI_M is always calculated
- RNC by PR; P (rain) or p (no-rain). If the "rain" and "no-rain" coexist within a footprint, it is treated as P (rain).
- R_PR (near surface rain rate estimates by PR); If the multiple PR pixels exist, R_PR is calculated as an unconditional average.
- SH (storm height); If the multiple PR pixels exist, SH is calculated as a conditional average of rain pixels.
- Convective / Stratiform classification by PR; If "stratiform" and "convective" pixels coexist, it is treated as "convective".

As a matter of convenience, RNC's by PR and TMI are denoted in combination. If the RNC by PR is P and RNC by TMI is t, for example, they are combined as Pt. The PR rain rate for Pt is, for example, denoted as R_PR[Pt]. It is obvious that R_TMI and R_PR are given as equation (3).

$$R\_TMI = R\_TMI[PT] + R\_TMI[pT] \quad (3\text{-}1)$$

$$R\_PR = R\_PR[PT] + R\_PR[Pt] \quad (3\text{-}2)$$

III. RNC Error and Retrieval Error

A. Definition

The total error ΔR is decomposed to be two terms: the error caused by inaccurate RNC and the error caused by inaccurate retrieval. The former is named as "RNC error" and denoted as ΔR_RNC and the latter is named as "retrieval error" and denoted as ΔR_RET. They are calculated by equation (4).

$$\Delta R\_RNC = R\_TMI[pT] - R\_TMI[Pt] \quad (4\text{-}1)$$

$$\Delta R\_RET = R\_TMI[PT] + R\_TMI[Pt] - R\_PR[PT] - R\_PR[Pt] \quad (4\text{-}2)$$

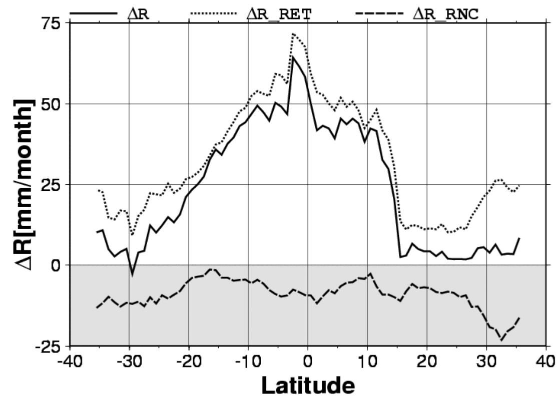

Figure 1. Zonal mean of ΔR, ΔR_RET, and ΔR_RNC [mm/month] for the 3-year data from Jan. 1998 to Dec. 2000.

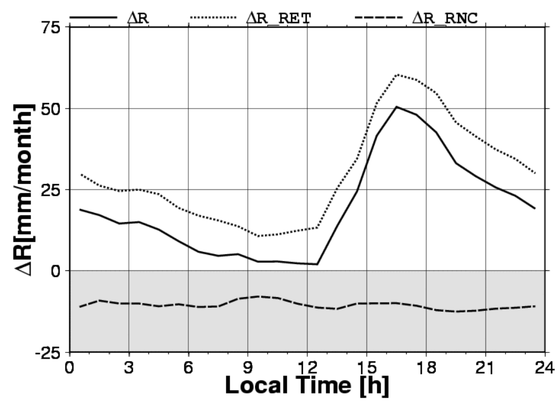

Figure 2. Same as Fig. 1, but for diurnal variation.

R_TMI[Pt] is originally not calculated, but calculated for this study as written above.

ΔR_RNC is the difference between the false rain rate when it is actually not raining and the missed rain rate when it is actually raining. If the RNC by TMI is perfect (perfectly agreed with the RNC by PR), ΔR_RNC is zero. While the RNC by TMI is not perfect, if the false rain rate and the missed rain rate is equally balanced, ΔR_RNC also becomes zero. When the RNC by TMI is not perfect, ΔR_RNC is dependent on the retrieval algorithm.

ΔR_RET is the difference of R_TMI and R_PR for all the raining cases. ΔR_RET is not dependent on RNC methods. This independence is the benefit by using the term R_TMI[Pt] in the definition.

If R_TMI[Pt] is not used, the RNC error and the retrieval error are defined as equation (5)

$$\Delta R\_RNC = R\_TMI[pT] - R\_PR[Pt] \quad (5\text{-}1)$$

$$\Delta R\_RET = R\_TMI[PT] - R\_PR[PT] \quad (5\text{-}2)$$

With this definition, ΔR_RET is dependent on the RNC method, because ΔR_RET evaluates the difference between R_TMI and R_PR only for PT case. Therefore, the former definition by equation (4) is adopted in this study.

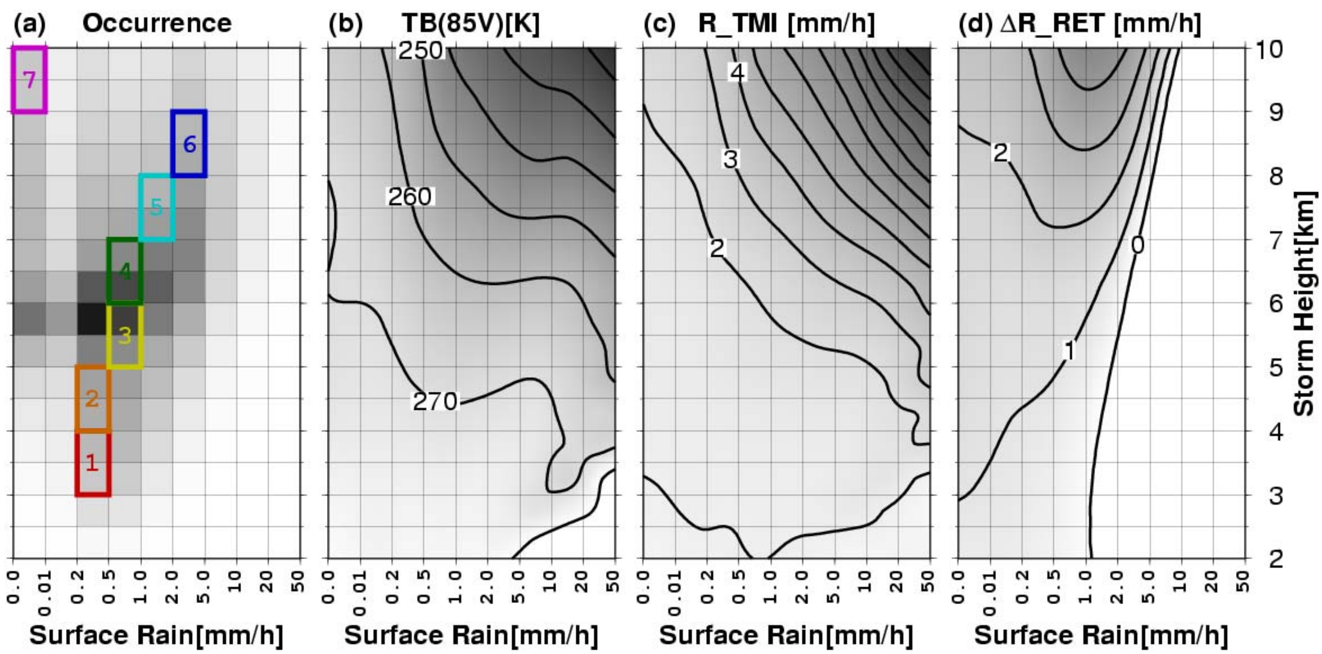

Figure 3. Statistics for storm height (SH) x surface rain (*R_PR*) categories, (a) the histogram of occurrence, (b) TB (85V), (c) *R_TMI*, and (d) for *ΔR_RET*.

B. Zonal Mean and Diurnal Variation

3-years PR and TMI data from Jan. 1998 to Dec. 2000 are used to calculate *ΔR_RNC* and *ΔR_RET* [mm/month]. Fig. 1 shows their zonal mean and Fig. 2 shows their diurnal variation. Generally, *ΔR_RNC* is negative (indicates underestimation of *R_TMI*) and *ΔR_RET* is positive (indicates overestimation of *R_TMI*). The absolute value of *ΔR_RET* is much larger than *ΔR_RNC*, then *ΔR* becomes positive. It should be noted that *ΔR_RET* which is calculated as an unconditional average tends to be larger when *R_TMI* and *R_PR* are larger. More detailed analysis for *ΔR_RET* is shown in the next section.

IV. Causes of Retrieval Error

A. Precipitation Characteristics

For the further analysis of the retrieval error, precipitation systems are characterized with the storm height (SH) and the rain rate (*R_PR*). Precipitation can be classified into one of 144 categories = 16 categories for SH (2km to 10km, each 500m bin) x 9 categories for *R_PR* (0, 0.01-0.2, 0.2-0.5, 0.5-1, 1-2, 2-5, 5-10, 10-20, 20-50 [mm/h]). Fig. 3 shows the results. The abscissa of each small figure is *R_PR* and the ordinate is SH. Fig. 3 (a) shows the histogram of occurrence. Positive correlation between SH and *R_PR* is seen with the exception of relatively high occurrence of high SH and zero *R_PR* precipitation systems. Fig. 3 (b) shows TB (85V). Generally, higher SH decreases TB (85V) much. In addition to the strong sensitivity to SH, TB (85V) is somewhat sensitive to *R_PR*. This relation is clear when SH is high. The direct relationship between *R_PR* and TB (85V) should be weak, because the effect of liquid rain rate on TB (85V) is easily saturated up to weak rain rate (~1mm/h). We hypothesize that the near surface rain rate and the rain rate above the freezing level are positively correlated. If so, the positive correlation between *R_PR* and TB (85V) can be explained.

Fig. 3 (c) shows *R_TMI* [mm/h]. In this figure, *R_TMI* is calculated as a conditional average. Similar with Fig. 3 (b), *R_TMI* shows sensitivity both with SH and with *R_PR*. It is natural because *R_TMI* is derived mainly from TB (85V). Fig. 3 (d) shows *ΔR_RET* [mm/h]. It is unavoidable that *ΔR_RET* have the sensitivity to SH for the fixed *R_PR*. The sensitivity to *R_PR* is not simple. When SH is low, *ΔR_RET* is positive for weak rain, but negative for strong rain. When SH is large, *ΔR_RET* is the largest around 1 [mm/h] of *R_PR*.

B. Diurnal Variation

As shown in Fig. 3 (a), 7 categories of (SH, *R_PR*) were chosen. For these categories, diurnal variation is examined. Fig. 4 (a) shows the number of occurrence for each one-hour local time bin. Low precipitation (such as category 1) appears in the early afternoon (around 12-15 LCT), but high precipitation (such as category 7) appears in the evening (around 18 LCT). Fig. 4 (b) shows TB (85V). It is interesting that diurnal variation is clearly seen even though each category has fixed SH and *R_PR*. TB (85V) takes the maximum in the early afternoon (around 12 -15 LCT) except for category 7. Black dotted line in Fig. 4 (b) indicates the TB (85V) under no-rain conditions. The width of diurnal variation is more than 10 [K] under no-rain conditions. Under rain conditions, the width of diurnal variation is smaller for lower or weaker rainfall and larger for higher or stronger rainfall. Category 6 shows approximately 10 [K] of diurnal variation. Category 7 shows no distinct diurnal variation.

It is clear that the reason of diurnal variation under no-rain condition is the diurnal variation of land surface brightness temperature which is mainly determined by land surface physical temperature. What is the reason of the diurnal variation under rain condition? The difference of the land surface brightness temperature does not reflect on the observed brightness temperature, if the liquid rainfall covers the land surface. The exception is the non-uniform rain within a footprint. In this case, the land surface information can affect the observed brightness temperature. Another possibility to explain the diurnal variation under rain conditions is the change of freezing height. In the daytime, the freezing height moves to high altitude, then the solid precipitation layer becomes thin for the same SH.

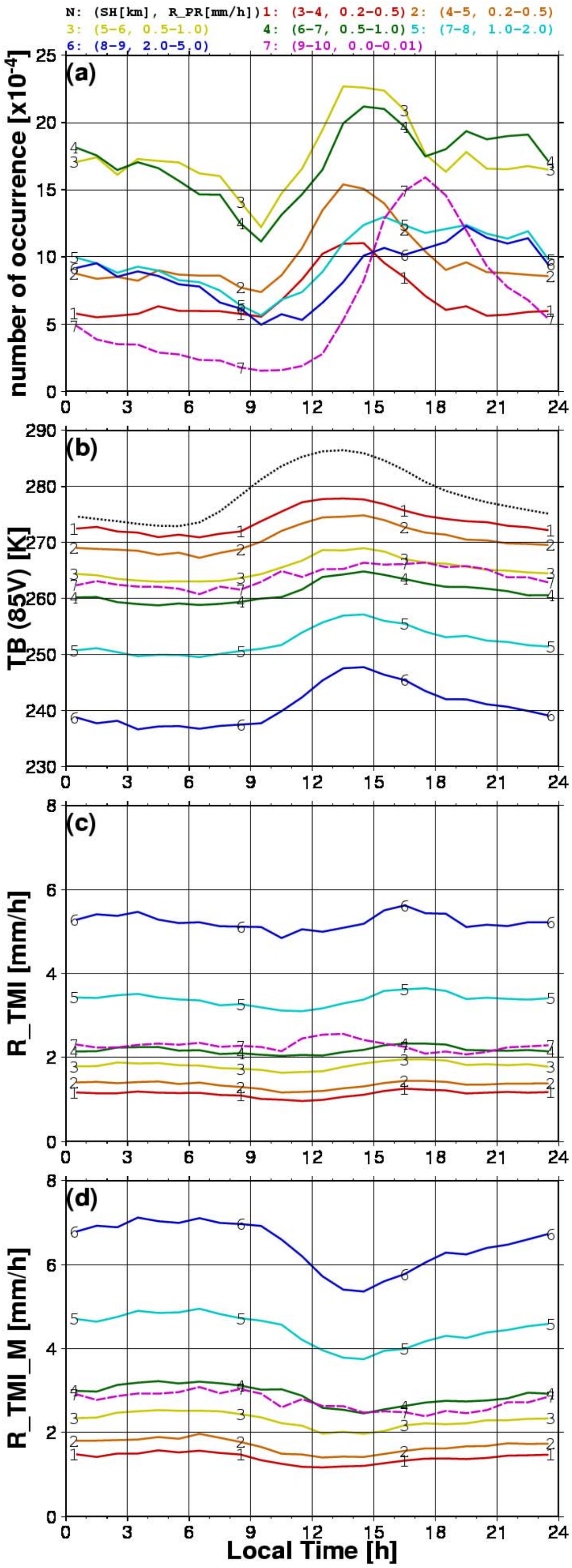

Figure 4. Diurnal variation of (a) the number of occurrence, (b) TB (85V), (c) R_TMI, (d) R_TMI_M for the seven categories, which is shown in Fig.3 (a). Number on the solid line denotes the number of category. Black dotted line in (b) is the statistics for “no-rain” case.

Fig. 4 (c) shows the diurnal variation of *R_TMI* [mm/h]. It seems strange that the diurnal variation of *R_TMI* is not agreed with the diurnal variation of TB (85V). Fig. 4 (d) shows the diurnal variation of *R_TMI_M* [mm/h], which is rather agreed with the diurnal variation of TB (85V). Every category except for category 7 takes the minimum *R_TMI_M* around 12-15 LCT same as TB (85V). The difference between *R_TMI* and *R_TMI_M* is the usage of CSI or not. CSI becomes higher in the daytime because of the TB (10V). This artificial diurnal variation of CSI can compensate the diurnal variation of TB (85V). Consequently, *R_TMI* for the fixed SH and *R_PR* does not clearly decrease in the daytime.

V. SUMMARY

The main source of *ΔR_RET* is storm height as Furuzawa and Nakamura [4] pointed out. This study finds that TB(85V) under rain conditions shows clear diurnal variation even if the storm height and surface rain rate are fixed. The phase of the diurnal variation is similar between under rain conditions and under no-rain conditions. The diurnal variation of land surface brightness temperature or freezing level are possible causes of the diurnal variation under rain conditions. The reason why TB (10V) is used to calculate CSI is thought to compensate the diurnal variation of TB (85V) under rain conditions.

ACKNOWLEDGMENT

This study is part of “production of a high-precision, high-resolution global precipitation map using satellite data (GSMaP)” supported by JST/CREST.

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