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# Significant impacts of the TRMM satellite orbit boost on climatological records of tropical precipitation

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With the unprecedented spaceborne precipitation radar (PR), the Tropical Rainfall Measuring Mission (TRMM) satellite has collected high-quality precipitation measurements for over ten years. The TRMM/PR data are nowadays extensively exploited in numerous meteorological and hydrological fields. Yet an artificial orbit boost of the TRMM satellite in August 2001 modulated the observation parameters, which inevitably affects climatological applications of the PR data and needs to be clarified. This study investigates the orbit boost effects of the TRMM satellite on the PR-derived precipitation characteristics. Both the potential impacts on precipitation frequency (PF) and precipitation intensity (PI) are carefully analyzed. The results show that the total PF decreases by 8.3% and PI increases by 4.0% over the tropics after the orbit boost. Such changes significantly exceed the natural variabilities and imply the strong effects of orbit boost on precipitation characteristics. The impacts on stratiform precipitation and convective precipitation are inconsistent, which is attributed to their distinct precipitation features. Further analysis reveal that the increased PI of stratiform precipitation is mainly due to the decreased frequencies of light precipitation, while the semi-constant PI of convective precipitation is caused by the concurrently decreased frequencies of light and heavy precipitation. A modification is applied to the post-boost PR precipitation data to retrieve the actual trends of tropical precipitation characteristics. It is found that the PI of total-precipitation approximately keeps invariable from 1998 to 2005. The total PF has no obvious trend over tropical oceans but decreases considerably over tropical lands.

**Tropical Rainfall Measuring Mission (TRMM), precipitation radar (PR), orbit boost, interannual variation, precipitation frequency, precipitation intensity**

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Precipitation plays a critical role in the hydrological cycle and energy transfer in the Earth-atmosphere system and is also the most momentous weather process that greatly affects human activities. Accurate precipitation measurements are thus of great importance. However, due to its intense variability both on temporal and spatial dimensions, the reliable global precipitation measurement is a historically challenging task. The difficulty is further exacerbated by the fact that the distribution of ground-based instruments throughout the globe is highly uneven, with very few measurements deployed over oceans and sparsely populated regions. Thanks to the advancements of aeronautic and remote sensing techniques, the global precipitation measurements have been now largely dependent on various precipitation sensors aboard the satellite platforms, which supply a real-time precipitation survey on a global scale.

The Tropical Rainfall Measuring Mission (TRMM) satellite, a meteorological low-inclination satellite designed for observing tropical and subtropical precipitation, was launched in November 1997 and has been continuously operating until today [1]. It carries aboard the first spaceborne active microwave instrument, i.e. precipitation radar (PR), which is deemed to be more reliable than any other spaceborne precipitation remote sensing means [2]. The PR has a unique capability of detecting 3-dimensional structures of precipitation and also can distinguish stratiform precipitation

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and convective precipitation on the pixel scale [3–5]. These functions make TRMM PR the most important spaceborne instrument for obtaining knowledge about global precipitation and latent heat [6–10]. In particular, its accumulated long-term record has been widely applied to climatological studies [11–17].

However, as the TRMM scientific products enter into more relevant fields, an issue becomes salient. This is related to the orbit boost of the TRMM satellite for prolonging the lifetime which occurring in August 2001. Due to the altitude change of the TRMM satellite orbit, from 350 to 402.5 km, a series of observation parameters are modulated, such as radar echo intensity, horizontal resolution, swath width, etc. A number of studies have devoted to investigate the effects of the TRMM satellite orbit boost on these technical parameters [18–20]. Some recent studies have also stressed the effects on precipitation retrieval algorithms [21, 22] as well as rainfall estimations [23–26]. A common consensus is that less monthly/daily rainfall amounts are measured by PR after the boost [23–26]. Such a reduction of rainfall amounts is attributed to several orbit-boost related causes [18,20,25,26].

Although a reduction of total surface rainfall has been recognized, the detailed variations of precipitation characteristics caused by the orbit boost are unclear up to now. For instance, a question is that the reduction of rainfall is contributed by a reduction of precipitation frequency (PF) or a reduction of precipitation intensity (PI) or the both. This knowledge is especially significant in precipitation climatology investigations. Meanwhile, the correction against the effect of orbit boost is of great importance for the extensive application of TRMM precipitation data and is particularly necessary for correctly interpreting the trend of precipitation. Therefore we attempt to clarify this question in this study, by further examining the effects of the TRMM satellite orbit boost on PF and PI. Moreover, PR-derived stratiform precipitation and convective precipitation are treated separately to gain in-depth understanding. Finally, we try to modify the PR precipitation data to reduce the impacts of orbit boost and retrieve the actual trends of tropical precipitation characteristics.

## 1 Data

The key parameters of the TRMM PR and their changes after orbit boost are shown in Table 1. As the altitude of the TRMM satellite increases from 350 to 402.5 km, the foot print size of the PR increases from 4.3 to 5.0 km at nadir, the signal intensity of radar echo decreases 1.2 dB (=20log(402.5/350)) [18,25], and the swath width gets 30 km wider.

The TRMM standard products 2A25, derived from the PR in eight boreal summers from 1998 to 2005, are used for analyzing the changes of near-surface rainfall rate caused by the orbit boost. The 2A25 algorithm classifies precipitation into three categories: stratiform, convective, and other-type precipitation [4].

**Table 1** Key parameters of the TRMM PR and their changes after the orbit boost

| | Pre-boost | Post-boost |
|---|---|---|
| Altitude (km) | 350 | 402.5 |
| Foot print size (km) | 4.3 | 5.0 |
| Detectable Z factor (dBZ) | 19.5 | 20.7 |
| Swath width (km) | 215–220 | 245–250 |

In order to highlight the impacts of the TRMM orbit boost on precipitation measured by the PR, the tropical regions (15°S–15°N) that have abundant rainfall are selected in this study. The boreal summer data are employed to eliminate the interferences from seasonal variations. In 2001, only the data before the orbit boost (from June 1 to August 7) are used.

## 2 Results

The interannual variations of precipitation frequency (the ratio of precipitating pixels detected by the PR to the total pixels detected) are presented in Figure 1. Statistical results show that both over tropical lands and oceans, the PFs of all the three precipitation categories decrease significantly after orbit boost. In order to quantify the unexpectedly large reductions, the 4-year averaged PFs of pre- and post-boost periods are compared (this method is also used in the following analysis). After orbit boost, the PF of stratiform (convective) precipitation decreases 0.27% (0.10%), corresponding to a relative reduction of 7.9% (8.7%). The PF of other-type precipitation decreases most notably and has a relative reduction of 58.9%. The total PF decreases 0.39% after the boost, and the relative reduction is 8.3%. Such decreasing amplitudes are extremely larger than natural variabilities, which should be attributed to the strong effects of the orbit boost.

The PI considered here is equivalent to conditional rainrate that reflects the average rainrate of rainy-pixels detected by the PR. Figure 2 shows the interannual variations of PI. After the orbit boost, the PI of stratiform and other-type precipitation increase evidently, but no obvious changes can be seen in convective precipitation. The PI of stratiform precipitation enhances 0.17 mm/h, corresponding to a relative increase of 8.2%. The PI of other-type precipitation enhances 0.11 mm/h (23.6%). The overall PI enhances 0.13 mm/h (4.0%) after the orbit boost. The combined effects of PF decrease and PI increase lead to a relative reduction of about 4.6% in the total surface rainfall measured by the PR, which is consistent with the results of monthly surface rainfall changes reported by Shimizu et al. [25].

In order to clarify the reasons for the above significant

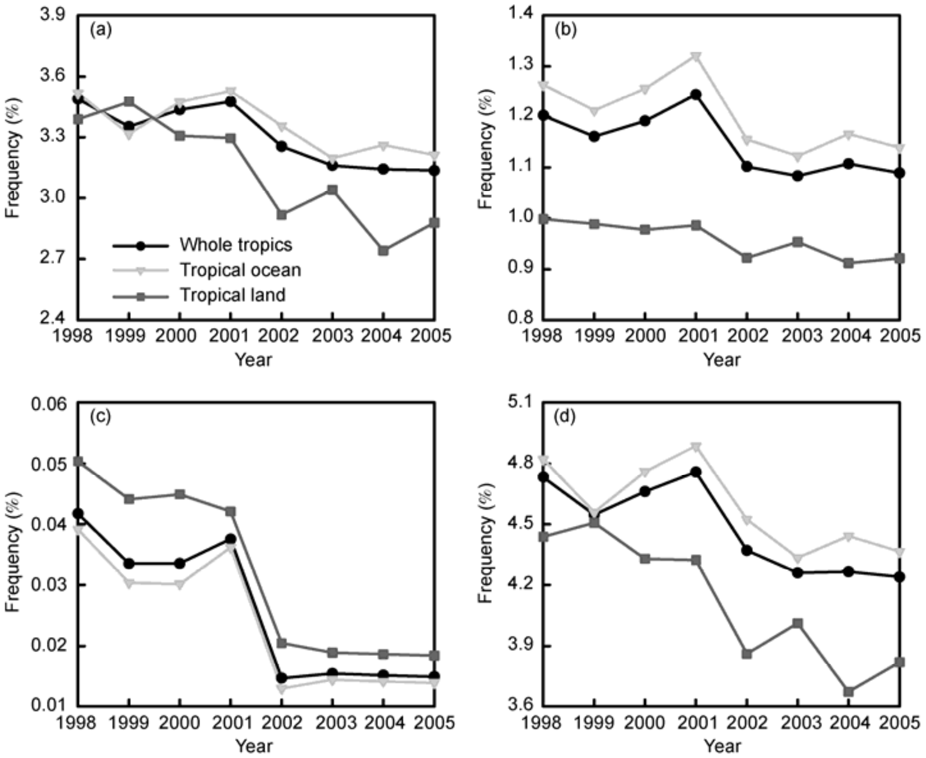


**Figure 1** Interannual variations of precipitation frequency for stratiform precipitation (a), convective precipitation (b), other-type precipitation (c), and all-type precipitation (d).

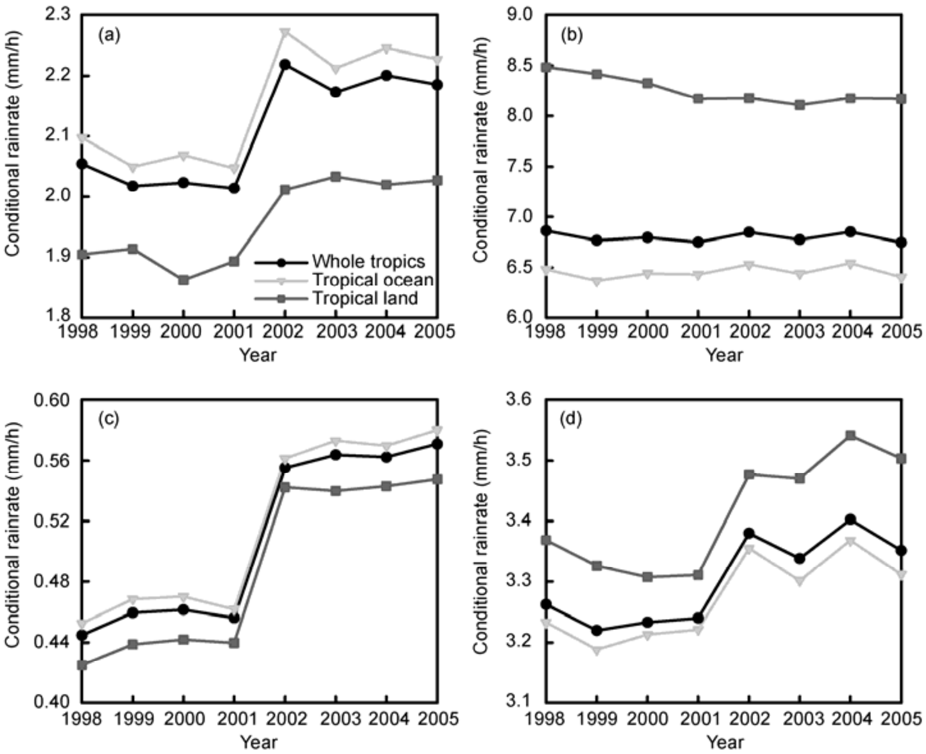


**Figure 2** Same as in Figure 1 but for conditional rainrate.

changes of PF and PI after the TRMM satellite boost, the PFs in different rainrate segments are investigated, as shown in Figures 3–5 for stratiform, convective and other-type precipitation, respectively.

After the boost, the PF of stratiform precipitation with rainrate less than 1 mm/h decreases significantly (~20%),

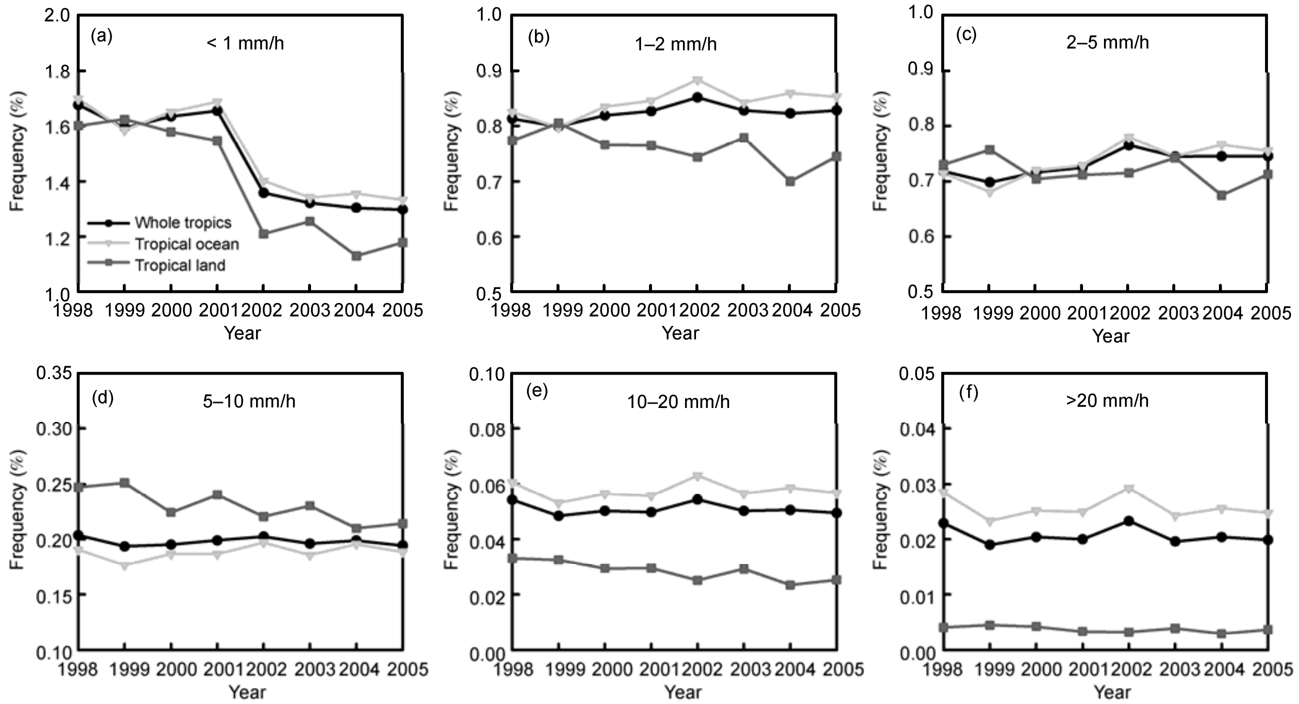


**Figure 3** Interannual variations of stratiform precipitation frequency in different rainrate segments.

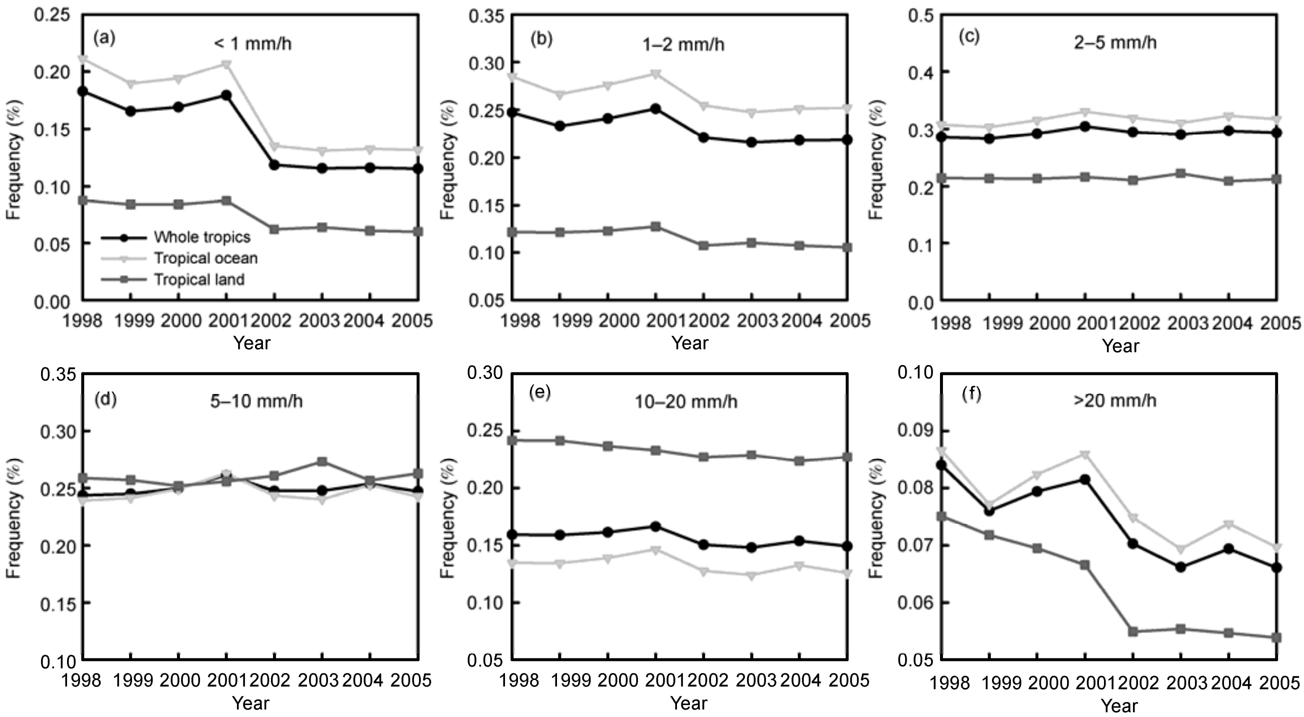


**Figure 4** Same as in Figure 3 but for convective precipitation.

and the PFs in other rainrate segments have no obvious changes. There are probably three reasons leading to the above phenomenon. Firstly, the signal intensity of PR decreases about 1.2 dB after the boost, resulting in that very light precipitation echoes cannot be detected by the PR any more [20]. Secondly, as the surface footprint size of the PR increases (from 4.3 to 5.0 km at nadir), the precipitation echoes at the edge of precipitating areas are more likely to be diluted by non-precipitating clutters and the light precipitation thus are easier missed by the PR. Meanwhile, the increase of footprint size makes the near-surface sampling heights increase at the edge of the PR swath, causing that the shallow rain systems (mostly light precipitation) are more often missed by the PR [25]. Thirdly, the increase of

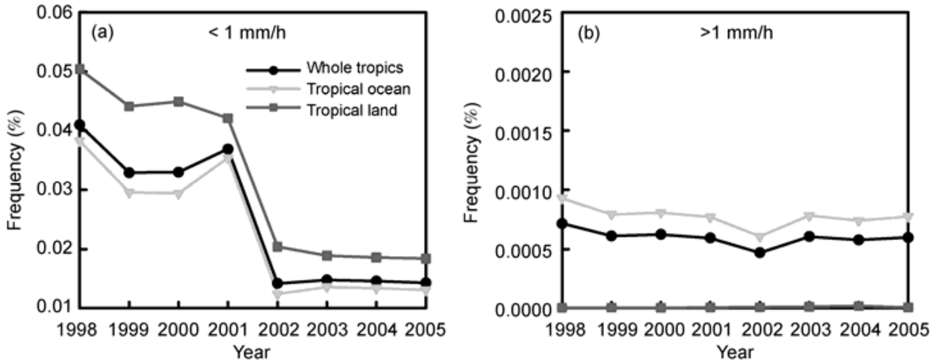


**Figure 5** Same as in Figure 3 but for other-type precipitation.

the TRMM satellite altitude results in a beam mismatch error [18,22,25], which also leads to the missed light precipitation.

The PFs of convective precipitation with rainrate less than 2 mm/h have evident decreases after the orbit boost. The PF with rainrate less than 1 mm/h has a relative reduction of nearly 1/3. The PF of 1–2 mm/h has a relative reduction of 10%. The reasons for the decrease of light convective PFs are similar to that of stratiform precipitation. The PFs of 2–10 mm/h have no obvious changes after the boost. Moreover, the PFs of heavy convective precipitation (heavier than 10 mm/h) have notable reductions, especially when the rainrate is heavier than 20 mm/h, which is consistent with the results of Nakazawa et al. [24]. The PF of 10–20 mm/h is relatively 7% less than that during the pre-boost phase. The PF with rainrate larger than 20 mm/h has a relative reduction of 15%, and the reduction is more obvious over land areas (~23%). Due to the different evolution regimes [27], the scales of convective precipitation are generally far smaller than that of stratiform precipitation. Also the non-uniform distributions of rainrate are more obvious for convective precipitation, especially over land areas, where the PFs are lower but the PIs are heavier than those over oceanic areas (as shown in Figures 1(b) and 2(b)). In principle, strong convective cores are mostly surrounded by relatively light precipitation. As the footprint size of the PR increases, the signals of heavy convective precipitation tend to be diluted by light precipitation. This leads to the notable reduction in the PR-derived PFs of heavy convective precipitation.

As shown in Figure 5, the rainrate of most other-type precipitation is less than 1 mm/h. Similar to stratiform and convective precipitation, after the orbit boost, the PF of other-type precipitation with rainrate less than 1 mm/h decreases obviously, and the relative reduction is even larger (~60%). Analysis shows that most other-type precipitation events show the feature of cumulonimbus anvils, which generally have very small rainrate and often arise at the edge of major precipitation areas [28]. Therefore, the impacts of signal intensity reduction and footprint size increase on other-type precipitation are more significant than on stratiform and convective precipitation. Just on the contrary, the PF of rainrate higher than 1 mm/h has no obvious change.

The PI spectrums in pre- and post-boost periods are presented in Figure 6. Statistical results show that the proportion of stratiform precipitation with rainrate less than 1 mm/h decreases significantly after the boost (~5%). Meanwhile, the proportions of 1–2 and 2–5 mm/h increase about 2%. The proportions of rainrate higher than 5 mm/h have no significant changes. The proportions of light and heavy convective precipitation both decrease after the boost, but increase for moderate precipitation. The proportion of convective precipitation with rainrate less than 1 mm/h is nearly 3% lower after the boost, and the proportions of 2–5 and 5–10 mm/h increase about 2%. Meanwhile, the proportion of rainrate highier than 20 mm/h decreases about 0.4%. The proportions of convective precipitation have no notable changes in other rainrate segments. After the boost, the proportion of other-type precipitation with rainrate less than 1 mm/h decreases about 1%. Because the reductions mostly occur in light precipitation segments, the PIs of stratiform and other-type precipitation measured by the PR increase significantly after the boost. But for convective precipitation, the proportions of light and heavy precipitation both decrease, resulting in that the PI of convective precipitation has no obvious change after the boost.

Apparently, such evident effects of the TRMM orbit boost, decreasing or increasing PF (PI), contribute much to the interannual signals and lead to the unrealistic long-term variations. In order to make the PR data appropriate for climatological applications, the actual trends of PF and PI are required. We attempt to reconstruct the data by eliminating interferes from the orbit boost.

The PR measurements during the pre-boost stage (1998–2001) are considered as the benchmark. In contrast, the PR measurements in the post-boost stage (2002–2005) have biases due to changes in instrumental and observational parameters, which determine the inherent biases in PF and PI. But the temporal variations of PF and PI in the post-boost stage are still reliable because the instrumental and observational parameters keep stable after the boost operation.

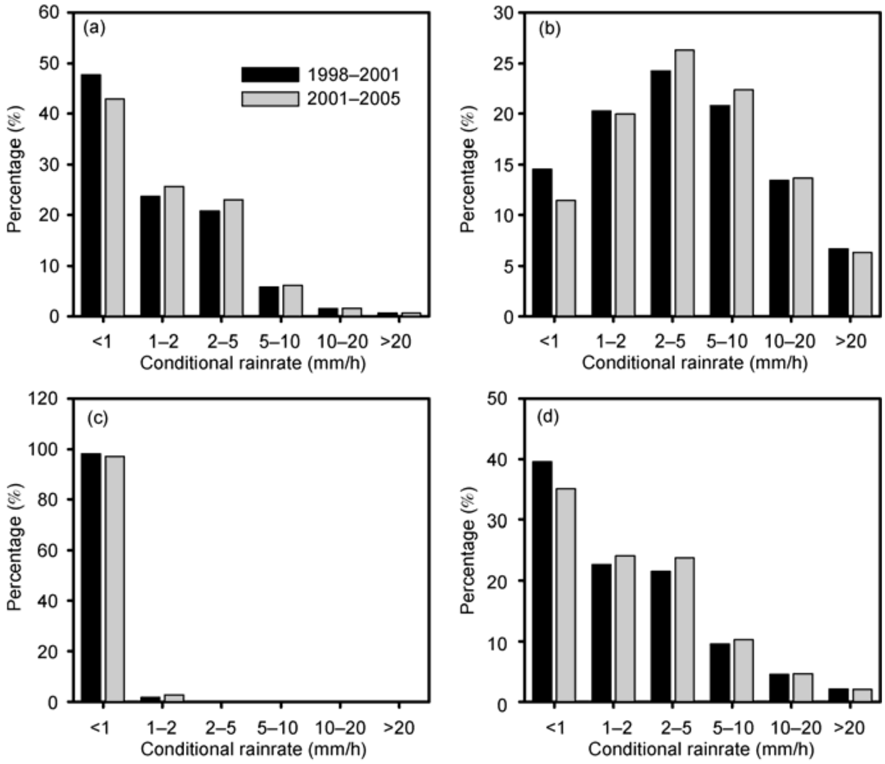


**Figure 6** Precipitation intensity spectrums of pre- and post-boost periods for (a) stratiform precipitation, (b) convective precipitation, (c) other-type precipitation, and (d) all-type precipitation.

Hence, the biases need to be corrected to link the variations of pre- and post-boost stages.

An explicit method is used to achieve the above purpose. Taking the total precipitation as an example, the linear fittings are applied to the data of pre- and post-boost periods, respectively, as shown in Figure 7(a) and (b). The resulting slopes reflect the actual natural variabilities during the respective periods, while the intercept of the latter fittings should be modified to eliminate the breaks caused by the orbit boost. This is achieved by directly adding the intercept differences between the two periods (Table 2) to the post-boost data. For instance, the PF (PI) in the post-boost period is modified by adding 0.35% (−0.14 mm/h) over the whole tropics.

After the correction, liner fittings are again applied to the total 8-year PF and PI sequences as shown in Figure 7(c) and (d), which are deemed to reflect the actual trends. It is indicated that the PIs almost keep unalterable both over topical oceans and lands. The PF has no obvious trend over tropical oceans but still decreases considerably over tropical lands (about 0.5% per decade). Such a considerable negative trend of PF over tropical lands is of great importance, which may need further research.

**Table 2** The intercept differences of precipitation frequency and conditional rainrate between pre- and post-boost periods

| | Whole tropics | Tropical ocean | Tropical land |
|---|---|---|---|
| Precipitation frequency (%) | 0.35 | 0.35 | 0.36 |
| Conditional rainrate (mm/h) | −0.14 | −0.14 | −0.18 |

## 3 Conclusions

The TRMM PR has accumulated precipitation measurements for over a decade, which is quite valuable for improving knowledge on the global precipitation climatology. But the TRMM orbit boost in August 2001 may act as an obstacle for the application of TRMM precipitation data and needs to be clarified. Effects of the TRMM satellite boost on PR-derived PF and PI are analyzed in this study. The major conclusions, especially useful for correctly interpreting the TRMM PR measurements, are summarized as follows.

(1) After the TRMM orbit boost, the total PF has a relative reduction of 8.3%. As more light precipitation events are missed by the PR than those of moderate and heavy precipitation, the total PI has a relative increase of 4.0%. These two effects jointly led to the 4.6% relative reduction of the PR-measured total surface rainfall. Such a rainfall reduction is not a true natural variability, but mostly an instrument-related bias caused by the orbit boost.

(2) For stratiform and other-type precipitation, the light precipitation events detected by the PR are greatly decreased, while the non-light precipitation events keep

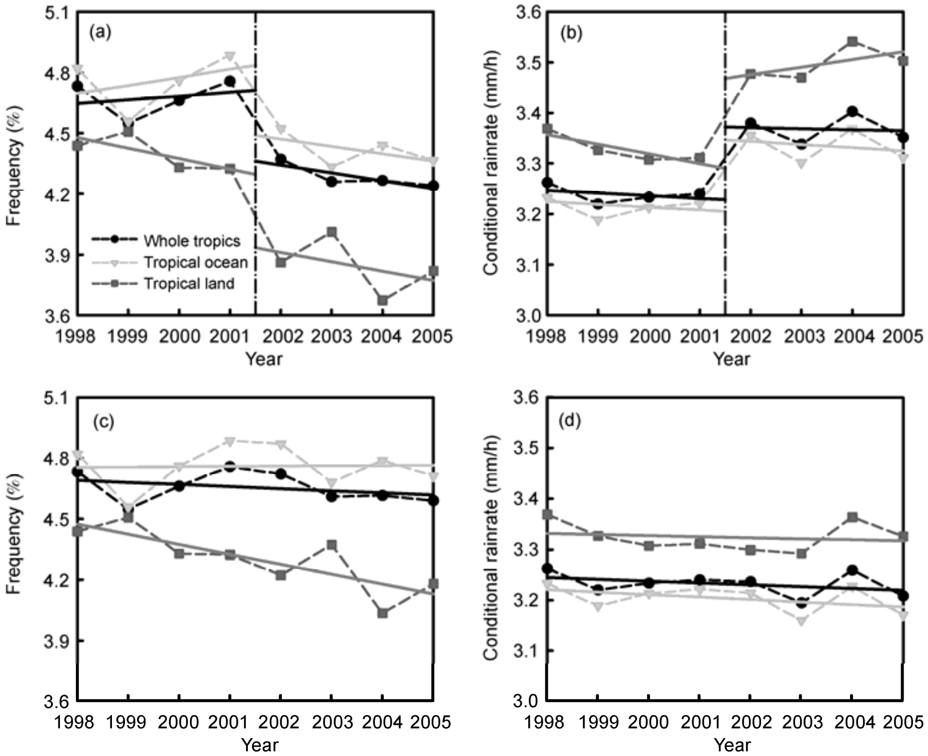


**Figure 7** Interannual variations of precipitation frequency ((a), (c)) and conditional rainrate ((b), (d)) before ((a), (b)) and after ((c), (d)) correction.

almost unchanging. As a result, the PI of stratiform and other-type precipitation has a relative increase of 8% and 24%, respectively.

(3) For convective precipitation detected by the PR, there are simultaneous reductions of light and heavy precipitation events. The rainrate spectrum thus concentrates on moderate values, but the PI is approximately constant. The unexpected considerable reduction of heavy convective precipitation events is probably attributed to their small-scale features and extremely non-uniform distribution of rainrate.

(4) After correcting the post-boost PR precipitation measurements, the natural variabilities of tropical precipitation during 1998–2005 are retrieved. Overall, the PIs almost keep invariable both over topical oceans and lands. The PF has no obvious trend over tropical oceans but decreases considerably over tropical lands at the rate of about 0.5% per decade.

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1 Kummerow C, Barnes W, Kozu T, et al. The Tropical Rainfall Measuring Mission (TRMM) sensor package. J Atmos Ocean Technol, 1998, 15: 809–817
2 Simpson J, Kummerow C, Tao W K, et al. On the Tropical Rainfall Measuring Mission (TRMM). Meteorol Atmos Phys, 1996, 60: 19–36
3 Kozu T, Kawanishi T, Kuroiwa H, et al. Development of precipitation radar onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. IEEE Trans Geosci Remote Sensing, 2001, 39: 102–116
4 Awaka J, Iguchi T, Okamoto K I. Rain type classification algorithm. In: Levizzani V, Bauer P, Turk F J, eds. Measuring Precipitation from Space: EURAINSAT and the Future. Heidelberg: Springer, 2007. 213–224
5 Fu Y F, Liu G S. Possible misidentification of rain type by TRMM PR over Tibetan Plateau. J Appl Meteor Climatol, 2007, 46: 667–672
6 Schumacher C, Houze R A. Stratiform rain in the tropics as seen by the TRMM precipitation radar. J Clim, 2003, 16: 1739–1756
7 Fu Y F, Liu G S, Wu G X, et al. Tower mast of precipitation over the central Tibetan Plateau summer. Geophys Res Lett, 2006, 33: L05802
8 He W Y, Chen H B. Analyses of evolution characteristics of a hailstorm precipitation from TRMM observations (in Chinese). Acta Meteorol Sin, 2006, 64: 364–376
9 Pan A J, Wan X F, Xu J D, et al. Barrier layer in the northeastern South China Sea and its formation mechanism. Chin Sci Bull, 2006, 51: 472–479
10 Liu C, Zipser E J, Nesbitt S W. Global distribution of tropical deep convection: Different perspectives from TRMM infrared and radar data. J Clim, 2007, 20: 489–503
11 Hirose M, Nakamura K. Spatial and diurnal variation of precipitation systems over Asia observed by the TRMM precipitation radar. J Geophys Res, 2005, 110: D05106
12 Fu Y F, Zhang A M, Liu Y, et al. Characteristics of seasonal scale convective and stratiform precipitation in Asia based on measurements by TRMM precipitation radar (in Chinese). Acta Meteorol Sin, 2008, 66: 730–746
13 Liu C, Zipser E J, Cecil D J, et al. A cloud and precipitation feature database from nine years of TRMM observations. J Appl Meteor Climatol, 2008, 47: 2712–2728
14 Liu Q, Fu Y F, Yu R C, et al. A new satellite-based census of precipitating and nonprecipitating clouds over the tropics and subtropics. Geophys Res Lett, 2008, 35: L07816

15 Zhu S X, Xu H M, Xu M M. Structure and distribution of rainfall over mesoscale mountains in the Asia summer monsoon region (in Chinese). Chin J Atmos Sci, 2010, 34: 71–82
16 Hu L, Li Y D, Song Y, et al. Seasonal variability in tropical and subtropical convective and stratiform precipitation of the East Asian monsoon. Sci China Earth Sci, 2011, 54: 1595–1603
17 Mao J Y, Wu G. Diurnal variations of summer precipitation over the Asian monsoon region as revealed by TRMM satellite data. Sci China Earth Sci, 2012, 55: 554–566
18 Takahashi N, Iguchi T. Estimation and correction of beam mismatch of the precipitation radar after an orbit boost of the Tropical Rainfall Measuring Mission satellite. IEEE Trans Geosci Remote Sensing, 2004, 42: 2362–2369
19 Cho H K, Chun H Y. Impacts on the TRMM data due to orbit boost in the spectral domain. Geophys Res Lett, 2008, 35: L01403
20 Short D A, Nakamura K. Effect of TRMM orbit boost on radar reflectivity distributions. J Atmos Ocean Technol, 2010, 27: 1247–1254
21 Awaka J, Iguchi T, Okamoto K I. TRMM PR standard algorithm 2A23 and its performance on bright band detection. J Meteord Soc Jpn, 2009, 87A: 31–52
22 Tagawa T, Hanado H, Shimizu S, et al. Improved correction of beam mismatch of the precipitation radar after orbit boost of the TRMM satellite. IEEE Trans Geosci Remote Sensing, 2009, 47: 3469–3479
23 Demoss J D, Bowman K P. Changes in TRMM rainfall due to the orbit boost estimated from buoy rain gauge data. J Atmos Ocean Technol, 2007, 24: 1598–1607
24 Nakazawa T, Rajendran K. Interannual variability of tropical rainfall characteristics and the impact of the altitude boost from TRMM PR 3A25 data. J Meteorol Soc Jpn, 2009, 87: 317–338
25 Shimizu S, Oki R, Tagawa T, et al. Evaluation of the effects of the orbit boost of the TRMM satellite on PR rain estimates. J Meteorol Soc Jpn, 2009, 87: 83–92
26 Chiu L S, Chokngamwong R, Wilheit T T. Modified monthly oceanic rain-rate algorithm to account for TRMM boost. IEEE Trans Geosci Remote Sensing, 2010, 48: 3081–3086
27 Houze R A. Stratiform precipitation in regions of convection: A meteorological paradox. Bull Amer Meteorol Soc, 1997, 78: 2179–2196
28 Fu Y F, Feng S, Liu P, et al. The cumulonimbus incus in summer Asia as detected by the TRMM PR (in Chinese). Acta Meteorol Sin, 2010, 68: 195–206