Changes in TRMM Rainfall due to the Orbit Boost Estimated from Buoy Rain Gauge Data

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ABSTRACT

During the first three-and-a-half years of the Tropical Rainfall Measuring Mission (TRMM), the TRMM satellite operated at a nominal altitude of 350 km. To reduce drag, save maneuvering fuel, and prolong the mission lifetime, the orbit was boosted to 403 km in August 2001. The change in orbit altitude produced small changes in a wide range of observing parameters, including field-of-view size and viewing angles. Due to natural variability in rainfall and sampling error, it is not possible to evaluate possible changes in rainfall estimates from the satellite data alone. Changes in TRMM Microwave Imager (TMI) and the precipitation radar (PR) precipitation observations due to the orbit boost are estimated by comparing them with surface rain gauges on ocean buoys operated by the NOAA/Pacific Marine Environment Laboratory (PMEL). For each rain gauge, the bias between the satellite and the gauge for pre- and postboost time periods is computed. For the TMI, the satellite is biased ~12% low relative to the gauges during the preboost period and ~1% low during the postboost period. The mean change in bias relative to the gauges is approximately 0.4 mm day$^{-1}$. The change in TMI bias is rain-rate-dependent, with larger changes in areas with higher mean precipitation rates. The PR is biased significantly low relative to the gauges during both boost periods, but the change in bias from the pre- to postboost period is not statistically significant.

1. Introduction

The Tropical Rainfall Measuring Mission (TRMM) satellite, a joint U.S.–Japan mission, was launched in November 1997. TRMM provides data from 40°N to 40°S, covering the Tropics and subtropics. TRMM is equipped with two primary instruments for measuring rainfall: the TRMM Microwave Imager (TMI) and the precipitation radar (PR). The TMI is a conically scanning microwave radiometer that operates at five different frequencies and provides information on several precipitation variables. Over the ocean the TMI 2A12 algorithm infers precipitation based on emission and scattering of microwave radiation at multiple wavelengths. Over land, TMI retrievals depend on ice scattering of short-wavelength radiation in deep clouds. As a result, the TMI retrievals are more directly related to surface rain over the ocean. The PR is an electronically scanning radar that measures backscattered radiation. It infers surface rainfall rates from the reflectivity profile near the surface. The TRMM instruments are described in more detail in Kummerow et al. (1998).

TRMM was originally launched into a low (350-km altitude) orbit to maximize the sensitivity and ground resolution of the instruments. The orbit was boosted from 350 to 402.5 km in August 2001 to reduce atmospheric drag and save maneuvering fuel, thereby prolonging the mission lifetime. The boost increased the swath width and field-of-view size for all of the instruments on the satellite. For the TMI, the swath width increased from 760 to 878 km, and the field of view from 4.4 to 5.1 km (at the highest resolution of 85.5 GHz). For the PR, the swath width increased from 215 to 247 km, and the nadir field of view from 4.3 to 5.0 km. In addition to an increase in the area of measurements, the change in the viewing angle at the earth’s surface affected certain other parameters, such as the emissivity of the ocean surface (Swift 1980). As a result, the orbit boost potentially affected the measurements in a variety of ways.

The goal of this study is to estimate the effects of the orbit boost on the TRMM rain-rate estimates. Because
changes in precipitation rain rates due to the orbit boost cannot be distinguished easily from real climatic variations, we compare the TRMM data to surface measurements of rainfall by rain gauges on ocean buoys, which are not affected by the orbit boost. The difficulty of this comparison is overcoming the sampling limitations of the two observing systems.

In addition to analyzing the orbit boost, we compare the TMI and PR instruments with each other. Previous work with the Version 5 TRMM data has shown that the bias between the TMI and gauges was near zero, while the PR was biased low with respect to the gauges (Bowman et al. 2003). Previous studies have also shown that the TMI typically measures more rainfall than the PR (Kummerow et al. 2000; Masunaga et al. 2002; Bowman et al. 2003; Serra and McPhaden 2003; Nesbitt et
al. 2004; Furuzawa and Nakamura 2005; Bowman et al. 2005). The retrieval algorithms were updated in March 2004 and data were reprocessed. Version 6 data products are used in this study.

2. Data

a. Buoy data

For ground truth, we use data from the National Oceanic and Atmospheric Administration (NOAA) Tropical Atmosphere Ocean (TAO)/Triangle Transocean Buoy Network (TRITON)/Pilot Research Moored Array in the Tropical Atlantic (PIRATA) ocean buoy array. The TAO Project began in the mid-1980s in an attempt to gain a better understanding of El Niño events. TAO/TRITON, which consists of 70 moorings in the tropical Pacific, was completed in December 1994. Since that time, buoy data are available throughout the tropical Pacific, although not all buoys carry rain gauges. For tropical Atlantic locations, buoys from PIRATA are used for analysis. The TAO/TRITON/PIRATA buoys are operated by the NOAA/Pacific Marine Environmental Laboratory (PMEL). Details of the rain gauge measurements can be found in Hayes et

Fig. 3. Scatterplots of TMI matches over the entire record at buoy 21 (5°N, 165°E). The time-mean rainfall rates are averaged in 6-h windows centered on TRMM overpasses. For clarity, the plot range does not include all data points. Fewer than 5% of the data points are outside of the plot range.
al. (1991), McPhaden et al. (1998), Serra et al. (2001), and Serra and McPhaden (2003).

In this project, rain gauges on buoys throughout the tropical Atlantic and Pacific Oceans are used for comparison with the satellite data. An advantage of these rain gauges over gauges on islands is that they are not affected by local orographic and land surface–heating effects, so they should be representative of open-ocean rain rates. Rain gauges remain the reference standard for precipitation measurement, despite possible interference due to varying exposure, wind effects, etc.

Thirty-six rain gauges with at least 8 months of data in both the pre- and postboost periods are used in this study; buoys with shorter data records are excluded. The buoys are numbered arbitrarily and are referenced by these numbers later in this paper (Fig. 1). The rain gauges are R.M. Young capacitance-type gauges that measure the volume collected in the gauge at 1-min intervals. A Hanning filter is used to smooth the noise in the volume measurements and produce filtered rain rates at 10-min intervals (Serra et al. 2001). Despite the filtering, instrument noise introduces some small positive and negative rain rates. Although unphysical, the negative rain rates cannot be removed without biasing the results, because the small positive rain rates cannot be unambiguously distinguished from real rain. Examination of the high-frequency data suggests that the mean of the rain rates due to noise is very close to zero.

**b. TRMM data**

Version 6 of the TRMM 3G68 data is used here. TRMM 3G68 data products are rain-rate estimates area averaged over 0.5° × 0.5° latitude–longitude grid boxes, resulting in 160 latitude grid boxes (40°S–40°N) and 720 longitude grid boxes. The satellite has a low-inclination orbit (35°) that precesses with respect to the diurnal cycle with a period of approximately 47 days.

The TRMM 3G68 products include the TMI (2A12 algorithm), PR (2A25 algorithm), and combined (3B31 algorithm) data products. We use only the TMI and PR products for comparison with rain gauges in this study. Results from the combined retrievals are very similar to those from the TMI. For some parts of the analysis we use monthly mean TMI data on a 0.5° × 0.5° grid (3A12 data product).

In this study we use TRMM TMI and PR data for the period January 1998 through May 2005. The TRMM 3G68 data are averaged over 1° × 1° boxes to assure that the buoys lie near the center of the grid boxes, as the buoy positions wander slightly due to necessary slack in the mooring cables. During the ~7.5-yr period analyzed in this study, approximately 3600 TMI and 1420 PR overpasses are available for a typical 1° × 1° grid box.

### 3. Methods

**a. Matching**

One difficulty in comparing TRMM and gauge data lies in the fact that gauges have high temporal resolution at a point, while TRMM data have low temporal resolution and broad spatial coverage. This is due to the fact that the satellite views a given location approximately once per day, while rain gauges have nearly continuous measurements. To provide the best possible comparisons, the buoy data are matched with TRMM overpasses.

The gauge data are time averaged in a 6-h window centered on each TRMM overpass. This time averaging provides near optimal comparison of the two observing systems (Bowman 2005), and the quality of the matches is not strongly dependent on the averaging interval. At some locations, there are substantial gaps in the gauge data; thus, there are usually many fewer matches at each buoy location than the actual number of TRMM overpasses.

| Table 1. Statistics of TRMM and buoy matched observations for buoy 21 (5°N, 165°E). All rain rates (mm day⁻¹). The % outside range is the percentage of nonzero values that were not plotted in the scatterplots and histograms. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                | TMI             | PR              | TMI             | PR              |
|                                | Gauge           | Satellite       | Difference      | Gauge           | Satellite       | Difference      |
| Number of matches              | 2652            | —               | —               | 1042            | —               | —               |
| % zeroes                       | 47.4            | 48.6            | 0.7             | 46.7            | 36.2            | 0.8             |
| % outside range                | 11.0            | 11.0            | 18.5            | 9.6             | 8.8             | 18.1            |
| Mean                            | 8.8             | 8.2             | −0.6            | 8.2             | 7.1             | −1.1            |
| Variance                        | 782.1           | 531.5           | 418.2           | 631.1           | 424.5           | 387.8           |
| Skewness                        | 3.6             | 3.8             | 3.1             | 3.6             | 3.7             | 3.0             |
| Kurtosis                        | 12.1            | 13.1            | 9.0             | 12.3            | 12.5            | 8.9             |
| Min                             | −4.4            | 0.0             | −266.7          | −4.3            | 0.0             | −147.7          |
| Max                             | 404.2           | 260.6           | 203.7           | 268.9           | 237.6           | 135.1           |
b. Orbit boost

In August 2001 the TRMM satellite orbit was boosted from 350- to 403-km nominal altitude. To evaluate the effects of the boost, the measurements from the buoys and satellite are separated into pre- and postboost categories. The period 7–24 August 2001 is omitted from the analysis. Biases are computed relative to the gauges. The preboost bias between the satellite and a single gauge is defined as Δr\text{pre} = ⟨r_{\text{TRMM}}⟩_{\text{pre}} − ⟨r_{\text{buoy}}⟩_{\text{pre}}, where angle brackets indicate the average over all matches, and the subscripts indicate the data source and time period. Similarly, the postboost bias is Δr\text{post} = ⟨r_{\text{TRMM}}⟩_{\text{post}} − ⟨r_{\text{buoy}}⟩_{\text{post}}. Finally, we subtract the preboost bias from the postboost bias to give the overall change in bias due to the orbit boost: Δr = Δr\text{post} − Δr\text{pre}. The rain gauge data are not corrected for possible wind or sea-spray effects. Because we compute the difference between pre- and postboost data, only changes in wind effects would have an influence on the gauge data, and we assume these effects to be small.

4. Results

a. Data availability

Figure 2 shows the record of data availability for each rain gauge over the study period. The solid black bars represent the periods in which gauge data are available at each buoy location. The single vertical lines represent the start and end of the TRMM data used in this analysis, and the double lines represent the start and end of the boost period.

TMI and PR data are available consistently throughout this time period, with only a few missing days. At the launch of the TRMM satellite in December 1997, only a few of the rain gauges were operating, but more gauges became available shortly after. Thus, most of the gauges did not observe the strong 1997/98 El Niño. Since TRMM data are almost continuous over the entire time period, the number of matches for each buoy location is primarily controlled by the gauge data availability.

b. Comparing single TRMM overpasses with gauge data

At each buoy the TRMM overpasses are matched with the 6-h time-mean gauge value, centered on the satellite overpasses. To illustrate, we show scatterplots and histograms of TMI and PR versus gauge data for the full mission for selected buoys in different precipitation regimes.

Buoy 21 is located at a climatologically wet location that lies in the intertropical convergence zone (ITCZ).
in the western Pacific (Fig. 3). The number of TMI matches for this particular location is 2652, of which 1362 are raining in the TMI observations. The gauge mean for buoy 21 is 8.76 mm day\(^{-1}\), while the TMI mean is 8.15 mm day\(^{-1}\). There are 1042 PR–gauge matches for this buoy, of which 665 are raining in the PR observations. The gauge mean is 8.17 mm day\(^{-1}\), and the PR mean is 7.09 mm day\(^{-1}\). The gauge means are different for the two instruments due to the different samples. Because of the differences between the observing systems, the percent time raining is not directly comparable between the gauges and the satellite.

Figure 4 shows histograms of the matched gauge and TMI data for buoy 21. Gauge values of less than 0.02 mm day\(^{-1}\) are considered zeroes for these histograms. Both the satellite and the gauge data are highly skewed to the right and highly leptokurtic (fat tailed). The bottom panels in Fig. 4 show the differences between the satellite and buoy matches (satellite minus buoy). For both the TMI and the PR, the distributions are skewed to the right (skewness \(\approx 3\)) and leptokurtic (kurtosis \(\approx 9\)). The differences between the gauge and the satellite have a central mode, although both instruments show positive biases of the satellite relative to the rain gauge, and the distributions are skewed to the right. Table 1 shows the statistics for buoy 21.

Figure 5 shows scatterplots of the TMI and PR matches with gauges at buoy 7. Buoy 7 lies outside of the ITCZ in the central Pacific in a generally dry location. At this location 2485 matches with the TMI yield a gauge mean of 0.03 mm day\(^{-1}\) and a TMI mean of 0.18 mm day\(^{-1}\). There are 981 PR–gauge matches, giving a gauge mean of 0.04 mm day\(^{-1}\) and a PR mean of 0.15 mm day\(^{-1}\) (Table 2).

c. **Comparing time means**

All of the available data matches at each gauge are used to compute time means for three time periods: the preboost period, the postboost period, and the entire mission. We discuss the TMI results first.

Scatterplots of time-mean values for each gauge are shown in Fig. 6. The diagonal gray line is the one-to-one relationship, while the solid black line is the linear, least squares fit to the TRMM–buoy match data. The dashed lines represent the 95% confidence limits on the fit, assuming Gaussian statistics. The change in the slope of the linear regression from preboost to postboost reflects the change in the bias discussed earlier. The correlation between the buoy and TMI data for all periods is high, with correlation coefficients \(r^2 \approx 0.97\). The slope for the TMI over the full time period is 0.95. The slope for the linear fit of the TMI preboost data is 0.88, while the postboost data have a slope of 0.99, showing very little bias relative to the gauges. The 95% confidence intervals are computed for each of the match plots, and only the TMI postboost fit is equal to one within the 95% confidence limits.

Table 3 shows the averages across all of the gauges. The TMI is biased low relative to the gauges during the preboost period (\(\sim 0.36\) mm day\(^{-1}\)), but the bias is essentially zero during the postboost period (0.03 mm day\(^{-1}\)). Assuming that the data are normally distributed, which is only approximately true, the pre- and postboost biases are statistically different at the 99% confidence level.

Figure 7 shows the change in bias at each gauge from preboost to postboost plotted as a function of the mean TRMM rainfall over the entire record. The left-hand plot, which shows the TMI change in bias versus the TMI mean rain rate at each gauge for the full period, illustrates the positive change in bias seen for the TMI. Although some gauges show a negative change in bias, the majority show positive changes, with larger changes at higher rain rates.

The same analysis is performed for the PR data. The PR–gauge scatterplots are shown in the right-hand pan-

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**Table 2. Statistics of TRMM and buoy matched observations for buoy 7 (0°, 140°W). All rain rates (mm day\(^{-1}\)). The % outside range is the percentage of nonzero values that were not plotted in the scatterplots and histograms.**

<table>
<thead>
<tr>
<th></th>
<th>Gauge</th>
<th>Satellite</th>
<th>Difference</th>
<th>Gauge</th>
<th>Satellite</th>
<th>Difference</th>
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<tr>
<td>Number of matches</td>
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<td>% zeroes</td>
<td>66.8</td>
<td>92.5</td>
<td>1.7</td>
<td>66.0</td>
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<td>% outside range</td>
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<td>0.1</td>
<td>0.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
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<tr>
<td>Mean</td>
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<td>0.2</td>
<td>0.0</td>
<td>0.2</td>
<td>0.1</td>
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<tr>
<td>Variance</td>
<td>1.6</td>
<td>4.4</td>
<td>3.3</td>
<td>1.0</td>
<td>0.7</td>
<td>1.3</td>
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<tr>
<td>Skewness</td>
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<td>3.3</td>
<td>2.9</td>
<td>3.0</td>
<td>3.1</td>
<td>2.9</td>
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<tr>
<td>Kurtosis</td>
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<td>7.2</td>
<td>7.4</td>
<td>8.4</td>
<td>7.4</td>
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<tr>
<td>Min</td>
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<td>−27.4</td>
<td>−1.8</td>
<td>0.0</td>
<td>−10.3</td>
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<tr>
<td>Max</td>
<td>31.2</td>
<td>85.9</td>
<td>54.6</td>
<td>14.0</td>
<td>14.4</td>
<td>14.3</td>
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</table>
The correlations between the buoy and PR data are slightly less than for the TMI, with $r^2$ values from 0.89 to 0.94. This can be attributed to the smaller PR sample sizes. The slope for the PR over the full time period is 0.76. The slopes of the PR pre- and post-boost data are 0.71 and 0.78, respectively. The PR sensitivity decreased as a result of the orbit boost and the greater distance from the satellite to the precipitation.

Fig. 6. Scatterplots of time-averaged TRMM and gauge rain rates from the matched values. The buoy rainfall rates are on the abscissa, and the TRMM rainfall rates are on the ordinate. (left) The scale for the TMI plots is 0–10 mm day$^{-1}$. (right) The scale for the PR plots is 0–12 mm day$^{-1}$. 
The loss of sensitivity is primarily for very light rain, however, which does not contribute much to the total, except in dry areas where the sampling errors are very large.

Histograms of the PR–gauge differences (Fig. 6, right-hand column) show that there are larger negative deviations of the PR from the gauge data than in the TMI data. The scatterplot of bias at each gauge versus rain rate (Fig. 7) does not reveal an obvious rain-rate dependence, although the statistics show a small positive change in the bias (Table 3).

The PR match means are shown in the right-hand columns of Table 3. The PR is biased low relative to the gauges during both the pre- and postboost periods, although the magnitude of the bias is smaller for the postboost period. The change in the bias of 0.22 mm day\(^{-1}\) is smaller than the TMI change of 0.39 mm day\(^{-1}\). The change in the PR bias due to the orbit boost is not statistically significant, even at the 90% confidence level.

Figure 8 shows a time series of the monthly mean oceanic rainfall rate from the TMI between 20°S and 20°N (TRMM 3A12 product). The black line represents the actual data, while the dashed line represents the pre- and postboost mean rainfall rates adjusted to remove the biases relative to the gauges. Because the bias is rain-rate dependent, the adjusted rate is calculated by dividing the TMI monthly mean rainfall values by the slope of the regression line in the respective boost periods. The vertical bar shows when the orbit boost occurred (7–24 August 2001). The horizontal lines represent the pre- and postboost mean rainfall rates. The mean rainfall rate of the raw TMI data over the ocean between 20°S and 20°N during the preboost period is 3.12 mm day\(^{-1}\), while the postboost mean is 3.22 mm day\(^{-1}\).

5. Summary and conclusions

The TRMM satellite orbit was boosted from ~350 to ~403 km in August 2001. The change in orbital altitude resulted in changes in a number of the satellite observing parameters, such as size of the fields of view and width of the orbit swath. In this study, rainfall estimates from the TMI and PR instruments on the TRMM satellite are compared with surface data from rain gauges on NOAA tropical ocean buoys in order to ascertain

<table>
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<tr>
<th>Table 3. Preboost mean, postboost mean, and boost change (postboost minus preboost) are shown for TRMM, gauges, and the bias (TRMM minus gauge). Means (mm day(^{-1})) are for all buoy–satellite matches.</th>
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<tr>
<td></td>
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<tr>
<td>Preboost</td>
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<td>TRMM</td>
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<td>Gauge</td>
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<td>Bias</td>
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Fig. 7. Change in bias from preboost to postboost (TRMM) for matched values. The TRMM mean rainfall rate over the entire period is on the x axis, and the change in TRMM bias from preboost to postboost is on the y axis.
whether the orbit boost resulted in systematic changes in the rain-rate retrievals.

To improve the comparison statistics, the rain gauge data are averaged in 6-h windows centered on the TRMM overpasses. Biases between the satellite and the gauges are evaluated by comparing the time-mean differences between the satellite and the gauges and by regressing satellite rain rates against the gauge rain rates. When the data are stratified into pre- and postboost periods, the TMI biases for the two periods are significantly different at the 99% confidence level. The biases are rain-rate dependent, with larger biases in regions with larger rain rates. The change in the PR bias due to the orbit boost is not statistically significant, even at the 90% confidence level, perhaps due to the smaller sample size for the PR. Similarly, the slopes of the linear regressions are statistically different for the TMI for the pre- and postboost periods, but not for the PR. Overall, the TMI data agree quite well with the gauges during the postboost period but are biased somewhat low during the preboost period. The PR is biased low with respect to the gauges by about 25% in both cases.

The time series in Fig. 8 shows the variation of mean rainfall as measured by the TMI from month to month over the ocean. The variation within any given year is approximately 0.5–1.0 mm day⁻¹. As expected from the regressions for the two periods, the postboost TMI data are much closer to the gauge-adjusted values than are the preboost data. The effect of the orbit boost is more clearly seen in the TMI data than in the PR data, as shown by the significantly higher change in the bias of the TMI data (Fig. 7).

By using the differences between the pre- and postboost biases, many potential sources of systematic error are reduced or eliminated. Nevertheless, the estimated biases due to the orbit boost could arise from several possible sources. The first is random error due to sampling. Rainfall is highly variable in space and time, the number of gauges is small, and, in this case, the record length is comparatively short. On the other hand, the systematic change in bias by the TMI across the set of rain gauges suggests that the shift is not simply due to sampling.

Second, a number of studies of the TRMM data show...
that there is a rain-rate-dependent bias between the TMI and PR instruments, suggesting that one or both instruments have a rain-rate-dependent bias relative to the true rainfall (Kummerow et al. 1998; Berg et al. 2002; Bowman 2005). This rain-rate-dependent bias could lead to an apparent orbit-boost effect either through systematic sampling error, such as a seasonal bias in the intervals of gauge operations, or through climatic variability. Unfortunately, it is not feasible to stratify the data by season due to the short length of the dataset. There are, however, known changes in the climate regime during the analysis period. During the pre-boost period, the climate went from a strong El Niño to a strong La Niña to approximately neutral. In the post-boost period the Pacific was in a weak El Niño phase. This kind of change is known to affect the intensity and distribution of rainfall across the Pacific. A real change in the precipitation could produce a change in bias due to the rain-rate dependence of the TRMM retrievals.

Third, the change in the TRMM data relative to the gauges could be due to changes in the retrieval algorithms. For example, due to the nonlinear dependence of the brightness temperature on rain rate, TMI observations must be corrected for nonuniform fields of view, a process referred to as the “beam-filling correction.” Changes in the size of the field of view require changes in the beam-filling correction.

With this study it is not possible to separate the possible sources of the bias. Good estimates of the absolute accuracy of the TRMM data will require better understanding of the accuracy of the rain gauges, larger and more complete gauge data records, longer time series that include a more complete range of climatic conditions, and a detailed understanding of the potential sources of bias in the retrieval algorithms. The gauge measurements are a unique and valuable source of information about the earth’s climate system, and efforts to expand their coverage and reliability will lead to long-term datasets of steadily increasing value.

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