Comparison of TRMM rainfall retrievals with rain gauge data from the TAO/TRITON buoy array

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[1] Long-term mean rainfall rates from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and Precipitation Radar (PR) are compared with in situ measurements by rain gauges on the NOAA TAO/TRITON buoy array in the tropical Pacific. The buoy rain gauges have an advantage over most of the available ground truth data in that they are not influenced by the local meteorological effects of islands. Instantaneous TRMM retrievals averaged over 1° × 1° longitude-latitude boxes are matched with 12-hour-averaged buoy rain amounts centered on the TRMM overpasses. The TMI has near-zero bias with respect to the gauges when compared across climatologically different gauge locations (dry to wet). The PR is biased about 30% low relative to the gauges. These results are consistent with other ground truth studies and the known biases between the TMI and PR in the TRMM version 5 algorithms. Because rain gauges are thought to underestimate rainfall during windy conditions, further study of gauge biases would be useful.

INDEX TERMS:

1. The Tropical Rainfall Measuring Mission

[2] The release of latent heat by condensation of water vapor is a major component of Earth’s energy budget and one of the main drivers of the global atmospheric circulation. Most of the latent heating and associated precipitation occur in the tropics. In order to study this critical component of the climate system, the centerpiece of the Tropical Rainfall Measuring Mission is a joint U.S.-Japanese satellite (referred to as TRMM) that was launched in November 1997 [Simpson et al., 1988]. Its primary mission is to measure precipitation in the tropics (+35°), especially over the tropical oceans, where surface observations are scarce.

[3] The principal precipitation measuring instruments on the satellite are the TRMM Microwave Imager (TMI) and the Precipitation Radar (PR). The instruments are described in Kummerow et al. [1998]. The TMI is a multi-channel, passive, conically-scanning, microwave radiometer. The TMI scans a swath ~758 km wide with resolution ranging from ~7 × 5 km to ~63 × 37 km, depending on frequency. The primary precipitation retrievals are based on emission of microwave radiation from raindrops, which appear warm against a cold ocean background. The TMI measures the volume-integrated emission by rain within the instrument’s instantaneous field of view, from which a surface precipitation rate can be inferred. The TMI is less effective over land surfaces due to variations in the surface emissivity. Because of its low altitude and relatively narrow swath (compared to polar-orbiting sun-synchronous satellites), the TMI requires between 1 and 2 days to provide complete coverage of the tropical region.

[4] The PR is the first space-based radar designed specifically to measure precipitation. It is a 13.8 GHz, pulsed, cross-track-scanning, phased-array system with a swath width of ~215 km. The PR provides high-resolution vertical profiles of precipitation systems and estimated surface precipitation rates with a nadir resolution of ~4.3 × 4.3 km.

[5] Satellite rainfall estimates have substantial random, and possibly systematic, errors; so it is important to validate satellite retrievals against other types of precipitation measurements, including ground-based radars and traditional rain gauges. Ground-based radars suffer from their own retrieval errors, so rain gauges remain a critical source of rainfall data. Passive microwave precipitation retrievals are more accurate over ocean surfaces than land, but precipitation measurements in the open ocean are scarce. Most ‘oceanic’ rain gauges are actually located on islands. Due to surface heating and topographic effects, even small islands can have significantly different mean rainfall rates than the surrounding ocean. Here we compare the long-term average precipitation rates retrieved by TRMM with in situ measurements by rain gauges on the TAO/TRITON buoys, which are moored in an array across the tropical Pacific Ocean [Hayes et al., 1991; Phillips, 2002]. A particular advantage of these data is that the gauges are not located on islands. The buoy rain gauges are possibly the cleanest ground truth comparison available for the TRMM satellite.

2. Data and Methods

2.1. TRMM Data

[6] We use the TRMM 3G68 data product, which consists of instantaneous rain rate retrievals area averaged over 0.5° × 0.5° longitude-latitude grid boxes (~50 × 50 km). The 3G68 data are not averaged in time. The 3G68 product includes three separate retrievals: TMI only, PR only, and combined TMI-PR. Here we present results from the separate TMI and PR products.

[7] The TAO buoys are moored at regular longitude and latitude coordinates that happen to lie at the corners of the 3G68 grid boxes (see Figure 1 below). To facilitate comparison with the gauges, we average the TRMM data

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The TAO/TRITON system is an array of moored buoys in the tropical Pacific Ocean operated by the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environment Laboratory [Hayes et al., 1991]. The buoys are used to collect oceanographic and meteorological data for monitoring, forecasting, and climate research, particularly El Niño/Southern Oscillation (ENSO) cycles. Over time, rain gauges have been included in the instrument suites on some of the buoys [Serra et al., 2001]. Figure 1 shows the locations of the 25 buoys equipped with rain gauges that are used in this study. The gauges are R. M. Young capacitance-type gauges that measure the water volume collected in the gauge. Data are collected at 1-minute intervals. Because rain rates are inferred from changes in the water volume of the gauge, noise in the volume measurements can result in small positive or negative rain rates. The noise is partially removed by filtering the data with a 16-point Hanning filter to produce smoothed 10-minute accumulations [Serra et al., 2001]. Rain rates are calculated by differencing the 10-minute data. Rain gauges in general are thought to underestimate rain due to wind effects at the mouth of the gauge [Koschmieder, 1934; World Meteorological Organization, 1962; Yang et al., 1998]. Undercatch errors during windy conditions can be large, the errors are not completely understood, and studies have not addressed the particular problems of rain gauges on ocean buoys [Serra et al., 2001].

3. Results
3.1. Data Availability and Averaging
[9] Tropical convective rain cells are typically much smaller than the 1° × 1° TRMM averaging boxes. Within a box of that size, rain cells grow, decay, and propagate with a time scale much less than the repeat time for TRMM measurements. Because the rain gauges make measurements at a point, while the TRMM makes area-averaged measurements over a sizable area, it is frequently the case that it is not raining at the gauge while TRMM detects rain elsewhere in the box. In order to provide an optimal comparison between these two observing schemes, we average the rain gauge data in time. Bell and Kundu [2003] use a theoretical model of rain tuned to observed rain rate statistics to show that there is an optimal combination of space and time averaging for such comparisons. In agreement with their results, we find that 12-hour averaging periods are close to optimal for 1° × 1° boxes, and that the results are not sensitive to moderate changes in the averaging period. Therefore, we average the 10-minute rain gauge data over 12-hour time periods centered on each TRMM overpass.

[10] For this study we use all of the available rain-gauge data for the first 4 full years of TRMM operation, 1998–2001. Figure 2 shows the availability of TRMM and buoy data for each buoy location by buoy number. The lower bar in each pair is the TMI availability, TRMM data is available for the entire 4-year period with few gaps of more than a day, but sampling is limited to about once per day, as the fine-scale structure indicates. Note that the sampling pattern depends on latitude.

[11] The solid black bars are the periods for which rain gauge data are available at each TAO buoy. The gauges generally operate for long periods with little missing data, but there are lengthy gaps between more-or-less contiguous periods of data. Only a few gauges were available at the time of the 1997–1998 El Niño. The number of TRMM overpasses for which buoy data is available is given on the right side of the graph for each buoy. This number ranges for 139 (buoy 20) to 1579 (buoy 23) and is primarily controlled by the availability of buoy data. Because of its narrower swath, the number of PR matches with buoy data ranges from 53 to 620.

3.2. Comparison
[12] Figure 3 shows comparisons of the time-mean precipitation rates as measured by the buoy rain gauges (abscissas) and the TRMM instruments (ordinates). The solid line indicates a 1-to-1 relationship. The mean precipitation over the period of record ranges from near zero at some buoy locations to ~10 mm/day at the wettest locations. Note that most of the gauges that were operating during early 1998, which included the end of the 1997–1998 El Niño, were located in the western Pacific (4, 9, 15, 18, and 23). Only a few gauges were operating at that time in the central and eastern Pacific (2, briefly; 20; and 22). Thus, the period of increased rainfall in the central and eastern Pacific associated with that El Niño was observed poorly by the gauges. The values in the scatterplots in Figure 3 are averages only over those periods for which gauge data is available. Because they do not include the effects of even one El Niño, they are not representative of the long-term time-mean rain rates in the central and eastern Pacific. (TRMM did observe the effects of most of the 1997–1998 El Niño throughout the tropics.)

[13] As Figure 3 shows, the correlation between the buoy and satellite data is very high and quite linear. The results of a linear, least-squares fit for each scatterplot are given in Table 1. The correlation coefficients ($r^2$) with respect to the buoys are 0.89 and 0.94, respectively, for the TMI and PR. The estimated intercepts are very close to zero. The estimated slope of the linear fit is 0.96 for the TMI, while the PR shows a noticeable low bias relative to the rain gauges.
This is consistent with the known biases between the TMI and PR of \( \sim 24\% \) in the TRMM version 5 algorithms used here [Kummerow et al., 2000; Masunaga et al., 2002].

4. Conclusions

One of the fundamental limitations of observing precipitation from low-Earth orbit is poor sampling. Sampling errors can be reduced, however, by averaging in space and/or time. This comparison between TRMM rainfall estimates and in situ rain gauge data shows remarkably good agreement when averaged over the periods of overlap. This is consistent with other TRMM ground truth studies [Kummerow et al., 2000; Adler et al., 2000, 2003]. The buoy rain gauges have the advantage that they represent open-ocean conditions and are not influenced by islands.

![Figure 2](image1.png)

**Figure 2.** Availability of TRMM TMI and buoy data for each buoy location. The lower bar of each pair is composed of short vertical lines for each TRMM overpass. The upper bars, which are generally solid black, indicate the periods during which more-or-less continuous 10-minute rain gauge measurements are available.

![Figure 3](image2.png)

**Figure 3.** Scatterplot of the time-mean precipitation at each buoy location as measured by the TMI (left) and PR (right). Each square represents the time-mean from a single rain gauge and the matched TRMM overpasses. The solid line is the one-to-one line. Wetter points are typically in the western Pacific, the intertropical convergence zone (ITCZ), or the South Pacific convergence zone (SPCZ). Drier points are in the eastern Pacific or outside the main convergence zones.
The bias between the TMI and buoy rain gauges is close to zero, while the PR is typically biased low with respect to the rain gauges. The next version of the TRMM algorithms (version 6) slightly reduces the long-term TMI means and increases the PR means (R. Adler, personal communication). Work is currently underway to analyze the seasonal and interannual variability in the rainfall and in the satellite-gauge differences.

While the biases between TRMM and the rain gauges are relatively small, the gauges themselves are thought to be biased low due to wind effects. If the gauges are in fact biased low, these results indicate that the TRMM retrievals would also be biased low. This suggests that further careful experimental study of the systematic errors in rain gauges would be worthwhile.

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References

Table 1. Least-Squares Linear Fits, TRMM vs. Buoy

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<tr>
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