Tropical Rainfall Distributions Determined Using TRMM Combined with Other Satellite and Rain Gauge Information

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ABSTRACT
A technique is described to use Tropical Rainfall Measuring Mission (TRMM) combined radar–radiometer information to adjust geosynchronous infrared satellite data [the TRMM Adjusted Geostationary Operational Environmental Satellite Precipitation Index (AGPI)]. The AGPI is then merged with rain gauge information (mostly over land) to provide finescale (1° latitude × 1° longitude) pentad and monthly analyses, respectively. The TRMM merged estimates are 10% higher than those from the Global Precipitation Climatology Project (GPCP) when integrated over the tropical oceans (37°N–37°S) for 1998, with 20% differences noted in the most heavily raining areas. In the dry subtropics the TRMM values are smaller than the GPCP estimates. The TRMM merged product tropical-mean estimates for 1998 are 3.3 mm day⁻¹ over ocean and 3.1 mm day⁻¹ over land and ocean combined. Regional differences are noted between the western and eastern Pacific Ocean maxima when TRMM and GPCP are compared. In the eastern Pacific rain maximum the TRMM and GPCP mean values are nearly equal, which is very different from the other tropical rainy areas where TRMM merged product estimates are higher. This regional difference may indicate that TRMM is better at taking into account the vertical structure of the rain systems and the difference in structure between the western and eastern (shallower) Pacific convection.

Comparisons of these TRMM merged analysis estimates with surface datasets shows varied results; the bias is near zero when compared with western Pacific Ocean atoll rain gauge data, but is significantly positive as compared with Kwajalein radar estimates (adjusted by rain gauges). Over land the TRMM estimates also show a significant positive bias. The inclusion of gauge information in the final merged product significantly reduces the bias over land, as expected.

The monthly precipitation patterns produced by the TRMM merged data process clearly show the evolution of the El Niño–Southern Oscillation (ENSO) tropical precipitation pattern from early 1998 (El Niño) to early 1999 (La Niña) and beyond. The El Niño-minus-La Niña difference map shows the expected eastern Pacific maximum, the “Maritime Continent” minima, and other tropical and midlatitude features, very similar to those detected by the GPCP analyses. However, summing the El Niño-minus-La Niña differences over the global tropical oceans yields divergent answers for interannual changes from TRMM, GPCP, and other estimates. This emphasizes the need for additional validation and analysis before it is feasible to understand the relations between global precipitation anomalies and Pacific Ocean ENSO temperature changes.

1. Introduction
Precipitation information is critical to understanding the hydrologic balance on a global scale and in understanding the complex interactions among the components within the hydrologic cycle. Rainfall information is especially important in the Tropics, because such a large fraction of the planet’s rain falls within low latitudes and because there are large variations therein that are related to climatic events [e.g., El Niño–Southern Oscillation (ENSO)]. In addition, our knowledge of rain
in the Tropics is limited due to poor conventional observations. The Tropical Rain Measuring Mission (TRMM) is remedying that situation by providing the most accurate global tropical rain estimates to date by using a unique combination of instruments designed purely for rain observation and by using a low-inclination orbit to provide excellent coverage of the Tropics. Details of the TRMM mission and instruments can be found in Kummerow et al. (2000).

The approach of this study is to utilize the high quality of the precipitation estimates that are available from TRMM as the calibrating mechanism to be applied to estimates made from other satellite platforms that have excellent time sampling. These adjusted estimates are then merged with information from rain gauge analyses over land into an integrated surface rainfall estimate over the global Tropics. This approach treats TRMM as the “flying rain gauge” and extends TRMM-like accuracy to space and time resolutions that are not available from TRMM alone.

This paper draws on the first two years (1998–99) of TRMM using the TRMM merged datasets to examine total tropical rainfall, seasonal and geographic distributions, and the impact of the 1997–99 ENSO events on the distributions. A key component of the analysis is comparison with the pre-TRMM state-of-the-art global precipitation analysis of the Global Precipitation Climatology Project (GPCP; Huffman et al. 1997). This is the first step in our long-term goal of using TRMM information to validate and improve the GPCP algorithms and analysis procedures, eventually allowing improvements in the entire 20-yr GPCP dataset. In addition, in this paper the TRMM merged analyses will be compared with surface-based estimates of monthly precipitation.

2. Technique to merge TRMM with other observations

As mentioned in the introduction, the TRMM data alone provide a uniquely accurate rainfall dataset. However, it is possible to use the high quality precipitation estimates from TRMM as the calibrating mechanism (the flying rain gauge) for estimates from other satellite platforms, which are then combined with rain gauge analyses. This scheme allows estimation of surface rainfall at finer timescales and space scales than is possible from TRMM alone.

Infrared (IR) data from geosynchronous satellites (geo-IR) are useful in estimating rain because they respond to the presence of clouds, especially deep convective clouds, and because they have excellent time/ space coverage. However, the physical connection between the IR radiances and the surface precipitation is relatively weak as compared with TRMM passive and active microwave sensors. For example, the Geostationary Operational Environmental Satellite (GOES) Precipitation Index (GPI; Arkin and Meisner 1987) assigns a single rain rate to all pixels colder than a specified temperature threshold. Adler et al. (1993, 1994) showed that biases in the GPI could be minimized by adjusting the GPI rain rate in space and time to some other sparse, but more accurate, estimate. In TRMM this adjusted GPI (AGPI) is produced by using cases of (nearly) coincident TRMM combined instrument [TCI]; the combined TRMM Microwave Imager (TMI) and precipitation radar (PR) algorithm; Haddad et al. (1997)] and visible and infrared scanner (VIRS) IR data to compute a time- and space-varying IR–rain rate relationship that matches (i.e., is “adjusted” to) the TCI-inferred rain rate. The use of (nearly) coincident TCI and VIRS IR data prevents sampling issues from affecting the derived relations. The adjusted IR–rain rate relationships are then applied to the full geo-IR data to take advantage of their superior time sampling. To the extent that the TCI estimates are unbiased, the bias of the AGPI ought to be small as well. The AGPI is produced operationally in TRMM as product 3B–42 by estimating the adjustment coefficients for calendar months on a 1° × 1° latitude–longitude grid, then calculating daily AGPI accumulations from the 3-hourly geo-IR data on the same grid. An example month of the key fields for AGPI is shown in the top three panels of Fig. 1. The TRMM TCI field in the top panel is relatively noisy due to the limited sampling of TRMM. The AGPI field in the second panel is limited by the characteristics of the IR-based algorithm, but contains eight samples per day from the geosynchronous satellites. The third panel shows the result of applying the adjustment coefficients derived from the TCI/VIRS data to the full geosynchronous dataset. This TRMM AGPI has the local bias of the TRMM TCI estimate and the high-frequency sampling of the geo-IR data.

The monthly TRMM and other data merged estimate is produced by merging the AGPI with information from rain gauges. The gauge analysis (the fourth panel in Fig. 1) used in this procedure is from the GPCP (Rudolf 1993). The merger is computed in two steps, following Huffman et al. (1997). First, the satellite estimate is adjusted to the large-area gauge information. For each grid box over land the AGPI estimate is multiplied by the ratio of the large-scale (5 × 5 grid box) average gauge analysis to the large-scale average of the AGPI estimate. Alternatively, in low-precipitation areas the difference in the large-scale averages is added to the AGPI value when the averaged gauge exceeds the averaged AGPI. This procedure keeps the bias of the merged product close to the (presumably small) bias of the gauge analysis on a regional scale, even while allowing the AGPI estimate to provide important local detail. Second, the gauge-adjusted AGPI estimate and the gauge analysis are linearly combined with inverse error–variance weighting. The errors employed in the combination are estimates of the (spatially varying) root-mean-square random error for each field, following Huffman (1997). The merged satellite/gauge product is
Fig. 1. Average precipitation (mm day$^{-1}$) for Jan 1998 for TCI (top), GPI from geo-IR data (top middle), TRMM AGPI (middle), GPCP rain gauge analysis (bottom middle), and TRMM merged analysis (bottom). Regions with black shading have no data.
produced operationally in TRMM as product 3B-43 for calendar months on a 1° x 1° latitude–longitude grid. The bottom panel in Fig. 1 contains the example of the final merged product. Over the ocean the results are identical to that of the third panel, with adjustments over land due to the influence of the rain gauges.

In the following discussions the focus will be on the analysis of the final merged product (fields of the type shown in the bottom panel of Fig. 1), although some comparisons with surface-based estimates will utilize the satellite-only AGPI product (Fig. 1, middle panel). A key part of the following analysis is a comparison with the standard merged product produced by the GPCP. The GPCP merged data product (Huffman et al. 1997) is a globally complete, monthly analysis at 2.5° x 2.5° latitude–longitude resolution using Special Sensor Microwave Imager (SSMI/I) microwave observations to adjust the geo-IR estimates in a method that parallels the TRMM-based approach described here. Gauge information is also included as a final step in a procedure nearly identical to that described earlier. The TRMM merged product and the GPCP analysis both use very similar procedures with different initial inputs, thus simplifying the intercomparison analysis.

3. The 1998 tropical rainfall totals and distribution for TRMM and GPCP

The TRMM merged analysis result for 1998 is shown in Fig. 2 along with the GPCP analysis for the same period. Both analyses have very similar patterns, as expected, with maxima in the ITCZ of the Pacific and Atlantic Oceans, in the eastern Indian Ocean, and over land areas in Brazil, Africa, and Indonesia. The relation of the patterns of 1998 to mean climate can be seen in Fig. 3, where the GPCP estimate for 1998 is compared to the 20-yr GPCP mean climate. The very distinct double ITCZ in the Pacific Ocean is unusual and is related to the rapid transition during 1998 from an El Niño to
a La Niña pattern, as discussed in detail in the next section.

The difference map in Fig. 2 (bottom panel) indicates mostly higher values for the TRMM merged analysis in the heavier rain areas of the tropical oceans. Over land the use of rain gauge information in both analyses produces a near-zero area-averaged effect, with some differences due to variations in gauge distribution and the difference in analysis resolution (2.5° for GPCP vs 1° for TRMM). Comparison of the gauge analyses at the two resolutions (not shown) confirms the resolution effect, although in areas of high rainfall the higher TRMM-based estimates may produce a slightly larger value. At the northeast coast of Brazil the alternating pattern of positive and negative differences in Fig. 2 (bottom panel) may be due to a combination of the difference in gauge and satellite analysis resolution and the presence of narrow bands of rainfall associated with squall lines propagating inland (Cohen et al. 1995; Garstang et al. 1994). Scatterplots of TRMM versus GPCP monthly values over the ocean (not shown) indicate that TRMM has higher values at higher rain amounts (greater than about 10 mm day$^{-1}$), whereas below 5 mm day$^{-1}$ GPCP has larger values in general. This reversal in TRMM/GPCP differences is also evident in Fig. 2, where TRMM is lower over the central Pacific at the equatorial rainfall minimum.

The zonally averaged profiles of oceanic rainfall (Fig. 4) clearly show the double ITCZ for 1998 with the peak values for the TRMM merged analysis being 15% higher than GPCP. Averaging over all oceanic areas in the latitude band 37°N–37°S yields a 10% difference for 1998 between TRMM and GPCP (Table 1). The mean values for oceanic regions are 3.3 and 3.0 mm day$^{-1}$ for TRMM and GPCP, respectively. Over ocean and land together, the TRMM merged analysis total is 3.1 mm day$^{-1}$ as compared to 2.9 mm day$^{-1}$ for GPCP.

The mean 10% difference over the ocean is not a constant but varies regionally. Figure 2 shows that the TRMM merged analysis is significantly higher in the
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Fig. 4. Zonal-average oceanic precipitation profiles (mm day\(^{-1}\)) for 1998 for TRMM merged analysis and GPCP merged analysis.

Table 1. Averages of oceanic, land, and total tropical (37\(^\circ\)N–37\(^\circ\)S) rainfall (mm day\(^{-1}\)) for 1998 for the TRMM and GPCP merged analyses.

<table>
<thead>
<tr>
<th></th>
<th>Ocean (mm day(^{-1}))</th>
<th>Land (mm day(^{-1}))</th>
<th>Total (mm day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRMM merged analysis</td>
<td>3.3</td>
<td>2.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Global Precipitation Climatology Project (GPCP) merged analysis</td>
<td>3.0</td>
<td>2.5</td>
<td>2.9</td>
</tr>
</tbody>
</table>

western Pacific, especially south of the equator, and in the eastern Indian Ocean and the eastern portion of the Atlantic ITCZ. From Figs. 2 and 4 TRMM is higher above 30\(^\circ\)N, especially east of Japan and the U.S. coasts. In the Southern Hemisphere midlatitudes, TRMM and GPCP means are nearly identical (Fig. 4), but TRMM has larger values just southeast of South Africa, Australia, and South America, with GPCP being larger to the east of those three locations. These midlatitude variations point to a possible difference in vertical structure from coastal waters (deeper convection) to the open ocean (shallower) that might be better detected by TRMM.

We investigated regional variations further by taking averages for 1998 over some smaller areas. Figure 5 displays locations of the seven numbered averaging boxes and the results are shown in Table 2. Boxes 2 and 3 in the western Pacific Ocean ITCZ and the South Pacific convergence zone (SPCZ) precipitation maxima display TRMM merged estimates that are significantly higher (>20%) than the GPCP estimates. However, box 4 in the eastern Pacific Ocean ITCZ has a very small (~4%) mean difference between the two. This eastern Pacific/western Pacific difference is probably related to the mean vertical structure of the rain systems, with those in the eastern Pacific being shallower. The TRMM estimates, which include information from the TRMM radar, may more accurately reflect the impact of the vertical structure on the surface rain estimate. Boxes 1 and 5 in the eastern Indian Ocean and Atlantic ITCZ show intermediate ratios, perhaps corresponding to somewhat intermediate cloud heights. For the more midlatitude boxes just to the east of Asia and South America the TRMM and GPCP estimates are close to each other with TRMM being slightly higher. These regional variations in the differences should be the focus of research with field experiment data or other information to determine if the TRMM estimates are better able to take into account the regional, structural differences in the convection.

The absolute values of the TRMM merged analysis in this study are driven by the TRMM TCI product that combines information from both the passive microwave and radar instruments (Haddad et al. 1997). This combination of sensor information should be the best TRMM-only absolute rain estimate when it is fully implemented. However, it is worthwhile to compare the TCI with the estimates made with the individual sensors. The four main TRMM-only estimates—two using the passive microwave information, one using the radar alone, and the TCI—are shown in zonally averaged format in Fig. 6. All four estimates agree reasonably well
with each other over most of the tropical zone with about a 20% spread among the four at the peak zonal value. The radar-based estimates are the lowest. Averaged over 20°N–20°S the percentage difference drops to 15%. The results therefore indicate that the TCI-based estimates are close to what would be obtained if a different TRMM source were used for computing the TRMM AGPI and merged analysis.

The TRMM merged analysis curve in Fig. 6 is identical to the TRMM AGPI because no gauges are used over water. The TRMM merged curve is based on the TCI, but has the eight-times-a-day sampling from the geosynchronous observations. Because the TCI, or any TRMM-only product, does not have uniform sampling over the diurnal cycle during a month, a TRMM-only estimate of monthly total rainfall may be different (and incorrect) from an estimate made from uniform sampling, even if the instantaneous observations from each sample have a small bias. This sampling effect explains the difference between the TCI and TRMM merged curves in Fig. 6 and indicates the need to be careful when using TRMM data alone for studying interannual or other variations based on monthly summations. Also, because both the TRMM merged analysis and the GPCP merged analysis use the sampling of the geosynchronous IR (calibrated by TRMM and polar-orbiting microwave observations, respectively) any differences are not due to sampling differences.

### 4. ENSO precipitation variations using monthly and daily TRMM $1\degree \times 1\degree$ merged analyses

Rainfall distributions in 1998, used in the last section for comparison of the TRMM and GPCP merged rainfall analyses, were considerably affected by El Niño and La Niña. Figure 3 (middle panel) shows the climatological mean annual pattern (using GPCP analyses) of primary ITCZ in the equatorial North Pacific Ocean, the SPCZ maximum in the equatorial South Pacific Ocean, and the maxima in the eastern Indian Ocean and the Atlantic ITCZ. The deviations from climatology for 1998 in the third panel of Fig. 3 show the very large excess of rain in the eastern Pacific, along and to the south of the equator. This positive anomaly is due to the early months of the year when the El Niño was nearing its end. As the La Niña became established in the latter part of 1998, the positive rainfall anomalies rapidly switched from the eastern Pacific to the “Maritime Continent” (MC), producing a positive anomaly in that area for the year. In between the two centers, in the western North Pacific and extending eastward, is a very strong rainfall deficit of over 3 mm day$^{-1}$. In effect the rapid transition between the El Niño and the La Niña in 1998 left this area very dry for 1998, the area along the equator at 160°E longitude having only 35% of its mean annual rainfall.

Figure 7 provides examples of the TRMM merged estimates for selected months in 1998 and 1999. The

### Table 2. Averages of rainfall (mm day$^{-1}$) for 1998 for seven sample regions (shown in Fig. 5) for TRMM and GPCP merged analyses.

The TRMM:GPCP ratio is also given.

<table>
<thead>
<tr>
<th>Box No.</th>
<th>Box size ($\degree$lat $\times$ $\degree$long)</th>
<th>TRMM (mm day$^{-1}$)</th>
<th>GPCP (mm day$^{-1}$)</th>
<th>TRMM:GPCP ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Indian Ocean, ITCZ</td>
<td>1</td>
<td>10 $\times$ 10</td>
<td>10.6</td>
<td>9.1</td>
</tr>
<tr>
<td>Western Pacific Ocean ITCZ</td>
<td>2</td>
<td>5 $\times$ 15</td>
<td>6.2</td>
<td>5.0</td>
</tr>
<tr>
<td>Western Pacific Ocean SPCZ</td>
<td>3</td>
<td>5 $\times$ 15</td>
<td>11.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Eastern Pacific Ocean ITCZ</td>
<td>4</td>
<td>5 $\times$ 15</td>
<td>7.6</td>
<td>7.3</td>
</tr>
<tr>
<td>Eastern Atlantic Ocean ITCZ</td>
<td>5</td>
<td>5 $\times$ 15</td>
<td>8.4</td>
<td>7.3</td>
</tr>
<tr>
<td>Northern Pacific Ocean</td>
<td>6</td>
<td>5 $\times$ 10</td>
<td>6.1</td>
<td>5.9</td>
</tr>
<tr>
<td>Southern Atlantic Ocean</td>
<td>7</td>
<td>10 $\times$ 10</td>
<td>4.9</td>
<td>4.4</td>
</tr>
</tbody>
</table>
sequence of maps for 1998 in Fig. 7 show that the distinct mean annual double ITCZ (Fig. 4) is mainly due to precipitation maxima above and below the equator at various times of the year. In January a single southern ITCZ exists in the very eastern part of the Pacific along with a large maximum in the western to central Pacific at 5°–10°S. In July and October the northern ITCZ is very active across the Pacific, and maxima in the Indian Ocean and in the SPCZ in the western Pacific at 5°S collectively add to the double ITCZ mean picture. In general the SPCZ is oriented more east–west than usual (July and October), reinforcing the zonal mean feature. In 1999, April shows the double ITCZ often seen there in this season, along with a weaker double feature in the Atlantic Ocean.

The transition from the peak of the 1997–98 El Niño at the start of 1998 and entry into the 1998–99 La Niña during the middle of 1998 is apparent in Fig. 7. An excellent description of the variations of various climate parameters, including precipitation, during 1998 is given by Bell et al. (1999). The TRMM-based fields in Fig. 7 show the southward shift of the ITCZ and eastward shift of the SPCZ in January 1998 during the El Niño. Then there is a dramatic clearing of precipitation along the equator as conditions return to normal (July 1998). Finally, the whole tropical Pacific pattern shifts westward as the La Niña sets in (October 1998). The rapid shift of the main, large-scale precipitation maximum from the central Pacific to the Maritime Continent during 1998 is responsible for the 1998 anomaly map as described in Fig. 3 (third panel) with the El Niño and La Niña maxima and a minimum located in between (just north of the equator, straddling the date line). As the La Niña continued to evolve in 1999 (Fig. 7), the area with the 1998 anomalous minimum did receive significant rainfall. These TRMM-based 1° × 1° latitude–longitude, monthly analyses will be valuable as tools for accurate monitoring of monthly precipitation and for model validation.

The impact of the 1997–99 ENSO events can be seen in the TRMM data by differencing the months of January, February, and March of 1998 (El Niño) from 1999 (La Niña) in Fig. 8. The huge precipitation maximum in the central Pacific during the first three months of 1998 disappears in late 1998 and into 1999, with most of the oceanic precipitation shifting to the areas surrounding the Maritime Continent and the western Pacific. There is also significantly greater rainfall in 1999 over Brazil and the Atlantic ITCZ to the east. The effect of these features is evident in the change map in the bottom panel of Fig. 8 with additional El Niño maxima (La Niña minima) evident eastward across the North Pacific above 30°N from China, the U.S. West Coast, the southeast United States, and the southern Indian Ocean. GPCP fields (not shown) reveal very similar patterns and similar magnitudes over most areas for this event. The change pattern in Fig. 8 is similar to that noted by Janowiak and Arkin (1991) for the 1987–88 El Niño–La Niña event using infrared-based satellite estimates. Huffman et al. (1997), using GPCP analyses,
Fig. 7. Average precipitation (mm day$^{-1}$) for selected months of 1998–99 for the TRMM merged analysis.
describe tropical anomalies associated with the 1992 El Niño event that are also very similar to those in Fig. 8, with the exception of areas in the Indian Ocean north of the equator and over eastern Africa. Most of the features in Fig. 8 also agree with those of Ropelewski and Halpert (1987, 1989), who examined precipitation patterns associated with ENSO over the last 100 yr using rain gauge data. Of particular note are the wet/dry, north/south dipoles over India and eastern Africa that show up in Fig. 8 mimicking the long-term gauge analysis.

A time history of the two areas of major rainfall perturbation (Fig. 9) from 1997 to 1999 using both GPCP and TRMM indicates the peaking of rainfall in the eastern Pacific (the Niño-3.4 box in Fig. 5) shortly after the peak in sea surface temperature (SST) in the same area. The TRMM estimates start at the rainfall peak of the El Niño in this Pacific location. Over the Maritime Continent (the MC box in Fig. 5) the rainfall decreases during the first half of 1997, reaches a minimum before the time of the eastern Pacific maximum, then increases steadily to a broad peak in the last half of 1998 and into 1999. The MC maximum is larger for the TRMM estimates than for GPCP, whereas in the Niño-3.4 box the difference is small. The effect of the 30–60-day oscillations can be seen in the high-frequency, month-to-month variations in rainfall in Fig. 9. It should be remembered that the TRMM merged dataset used here has the sampling of the geosynchronous IR data (eight times a day); therefore, there are no aliasing problems as might be the case when using only the TRMM satellite data. For additional information on ENSO tropical rainfall perturbations and their evolution using the GPCP datasets, see Curtis and Adler (2000) for a discussion of ENSO rainfall indices and their relation to SST-based and other ENSO indices.

A finer-scale view of the El Niño-to-La Niña evolution is shown in Fig. 10 using the TRMM daily, 1° by 1° latitude–longitude AGPI product. The time–longitude diagram for mean rainfall over 5°N–5°S displays...
the large-scale maxima of the El Niño and La Niña, and the very rapid shift between them from 120°W to 120°E during May 1998. At smaller scales one can see the eastward propagation of the 30–60-day oscillations during the January–April 1998 period. These events include a strong, very continuous precipitation maximum nearly encircling the globe during May 1998, at the beginning of the La Niña phase, which may be related to the transition (Takayabu et al. 1999). During the La Niña, from June 1998 to January 1999 the predominant propagation direction from the Maritime Continent across the Pacific and into the Atlantic is from the east. These characteristics and others discernible with finer-scale products, such as shown in Fig. 10, will help to understand better the evolution of these climate-scale events.

Last, recent work by Soden (2000) and Robertson (1999, personal communication) has raised important questions about the variation of integrated tropical, oceanic rainfall during ENSO events. Figure 11 shows such integrated values for a number of estimates during 1997 and 1998, including the TRMM merged product starting in January 1998. The GPCP estimates show a slight rise during El Niño and then a drop during 1998 and into 1999 as the La Niña develops. The TRMM merged analysis shows a very different pattern starting in 1998 with no decrease in integrated precipitation during 1998 and 1999. Even within the TRMM-based products there is a difference. The TMI product (TRMM product 2A-12) shows a significant decrease from early 1998 to early 1999, followed by approximately constant values in the middle of 1999, significantly less than in early 1998. The TRMM PR surface product (3A-25) shows roughly constant values during the period. The combined radar-radiometer product (TCI; TRMM product 3B-31) generally follows the merged product and also has no significant trend during this period. Remember that the TCI is used to calibrate the geosynchronous IR observations in the TRMM merged product (3B-43). When the geographic distribution of the changes shown in Fig. 11 are diagnosed, the results indicate that the differences in the trend are concentrated in an arc running from the Indian Ocean through the Maritime Continent to the eastern portion of the SPCZ. In 1999 this was the area of heavy rainfall where the TRMM merged estimate was significantly higher than the other estimates. The differences in trends may, therefore, be related to a subtle change in the structure of the rainfall as the rain maximum shifts from the central Pacific to the west from early 1998 to early 1999. The change in vertical structure may be treated differently among the various products resulting in the observed differences.

The variations among the different products suggest we should be very careful at this time in trying to relate the magnitude of precipitation variations to temperature variations related to ENSO and to global warming.

5. Comparison of TRMM-based estimates with surface-based estimates of precipitation

Comparison of TRMM-based estimates of rainfall with independent, surface-based measurements over both ocean and land is a key component of understanding the validity of the TRMM estimates. In this section three surface-based datasets are compared with the
TRMM merged estimates (TRMM product 3B-43, version 4). Depending on the case, the comparison is made on a 1° space scale and on a 5-day or 1-month timescale.

Oceanic validation data, of course, are very limited. For this study two main datasets are used. First, monthly atoll rain gauge data from the Comprehensive Pacific Rainfall Data Base (Morrissey et al. 1995) for the period January 1998 to May 1999 were used. These monthly data, which cover portions of the western Pacific Ocean, were analyzed in 2.5° × 2.5° latitude–longitude boxes to make the analysis comparable to the GPCP analysis grid and provide some spatial smoothing. The TRMM 1° × 1° latitude–longitude analysis is smoothed to 2.5° for comparison. The TRMM merged product and GPCP
estimates show significant scatter in comparison with the atoll rain gauge analysis (Fig. 12), but a near-zero positive difference (1 mm month$^{-1}$) for the TRMM merged analysis and a larger, negative difference for the GPCP analysis ($-26$ mm month$^{-1}$). The mean atoll rainfall is 175 mm month$^{-1}$, so the GPCP is 15% low, similar to the results reported by Huffman et al. (1997). If the atoll rain gauge estimates are representative of the open ocean surrounding the atolls, these statistics would lead to a tentative conclusion that the TRMM estimates are very good in terms of absolute magnitude.

The second oceanic dataset is the TRMM validation program analysis of surface-based radar data at Kwajalein Atoll in the western Pacific Ocean. The radar data are quality controlled and adjusted to rain gauges on the atoll along the lines described by Rosenfeld et al. (1995). The Kwajalein surface information is available as pentad (5 day) accumulations and is therefore compared to the TRMM AGPI on that timescale (Fig. 13). Only pentads with more than 90% of the surface radar data available are used in this exercise. The Kwajalein data were averaged to the TRMM $1^\circ \times 1^\circ$ latitude-longitude grid. The TRMM merged estimates indicate a significant positive bias relative to the Kwajalein surface data, 2.4 mm pentad$^{-1}$, a 19% difference.

In order to make comparisons with the Kwajalein surface estimates on a monthly scale and include the GPCP estimates (only available on a monthly scale) the available matched (surface radar and TRMM) pentads are scaled to monthly totals based on the number of pentads (days) for that month. Also, the GPCP is interpolated to a $1^\circ$ grid. This procedure allows for monthly comparisons and is valuable for bias comparisons between TRMM and GPCP. The monthly result (Fig. 14) is a 21% positive bias for the TRMM AGPI and a 6% negative bias for interpolated GPCP monthly results.

Thus, the limited oceanic comparison data that are available provide conflicting results. The TRMM merged estimates are nearly unbiased according to the atoll gauge data, but the Kwajalein radar observations (adjusted by gauges) suggest that the TRMM estimates are high. The GPCP estimates, on the other hand, are low compared to the atolls and roughly match the Kwajalein results. Given the lingering questions about how representative atoll reports are of the open ocean and the preliminary nature of the radar analysis, we are left without strong independent confirmation of the TRMM estimate of rainfall magnitude. It is hoped that this situation will improve with additional analysis of the Kwajalein radar data and other oceanic radar data and the study of the impact of the atolls on the local precipitation patterns.

Radar coverage at the remaining two TRMM primary ground validation sites (Houston, Texas, and Melbourne, Florida) is mostly situated over land. Thus, the data from these sites are utilized for overland comparison. The scatterplots for the these two sites (Fig. 15) for pentad periods of TRMM AGPI (TRMM product 3B-42) show a positive bias of the TRMM-based estimates relative to the gauge-adjusted, surface radar estimates. At Houston the bias is about 5 mm pentad$^{-1}$ (30%) and at Melbourne it is 9 mm pentad$^{-1}$ (47%).
order to make a comparison on a wider geographic scale, the GPCP gauge analysis that is used in the final TRMM merged product is used here for comparison with the satellite-only product. A comparison is done over the global Tropics for all 1° boxes in which there are at least two gauges (Fig. 16a). This analysis confirms the positive bias (28%) of the TRMM AGPI estimates relative to the gauge analysis.

The final TRMM merged analysis (TRMM product 3B-43) includes GPCP gauge information over land and displays the expected dramatic reduction in variance and bias when it is compared with the GPCP gauge analysis as a check (Fig. 16b). A similar comparison to the Houston and Melbourne ground validation data (Fig. 17) shows a similar result, even though there is only a small overlap in the ground validation and GPCP gauge sites. However, especially at Melbourne, the bias is still significant, and both the satellite results and the validation data need additional analysis to refine the relations and lead to improved satellite estimates.

6. Recent version-5 TRMM results

The results in this paper are based on version-4 TRMM operational algorithms and products. In November 1999 the version-4 algorithms were replaced by version 5 in real-time processing and reprocessing of TRMM data from the beginning of the mission was begun using version-5 algorithms. Analysis of the 7 months of versions-4 and -5 overlap (January–July 1998) available indicates that the resulting version-5 TRMM merged analysis (TRMM product 3B-43) is significantly lower (18%) than version 4. This decrease is due to a decrease in the combined radar–radiometer product (3B-31). TRMM radiometer and radar only products also changed, but to a much smaller degree. The decrease is fairly uniform both geographically and as a function of rainfall magnitude. The trends and other time variations described in this paper do not change significantly, but the absolute magnitude of the rainfall should still be considered preliminary.
7. Conclusions

The technique to use TRMM information to adjust other satellite data and combine with rain gauge information over land has been shown to be useful to derive finescale (1° × 1° latitude–longitude) monthly analyses. Comparison of TRMM merged analysis estimates (version 4) with surface datasets shows varied results when compared with atoll rain gauge data (near-zero bias) or Kwajalein radar (adjusted by rain gauges) estimates (significant positive bias). Over land the TRMM estimates show a significant positive bias. The inclusion of gauge information in the final merged product significantly reduces the bias over land. However, recent results from version 5 of the TRMM products reemphasizes that the absolute value of the rainfall is preliminary and in need of careful examination and validation.

The TRMM merged estimates (version 4) are 10% higher than those from the Global Precipitation Climatology Project (GPCP) when integrated over the tropical oceans (37°N–37°S) for 1998, with 20% differences noted in most heavily raining areas. In the dry subtropics the TRMM values are smaller than the GPCP estimates.
The TRMM merged product tropical estimates are 3.3 mm day\(^{-1}\) over ocean and 3.1 mm day\(^{-1}\) over land and ocean combined. In the eastern Pacific rain maximum the TRMM and GPCP mean values are nearly equal, which is very different from the other tropical rainy areas where TRMM estimates are higher. This regional difference may indicate that the TRMM merged product is better at taking into account the vertical structure of the rain systems and the difference in structure between the western and eastern (shallower) Pacific convection.

The monthly patterns produced with the TRMM merged data process clearly show the evolution of the ENSO tropical precipitation pattern from early 1998 (El Niño) through early 1999 (La Niña) and beyond. The El Niño-minus-La Niña difference map shows the eastern Pacific maximum, the Maritime Continent minima, and other tropical and midlatitude features, very similar to those detected by the GPCP analyses. In particular, the finescale TRMM merged analysis shows distinct features over the continents with positive differences over southeastern South America, eastern Africa, eastern China and southern Japan, northern India, and the southeastern United States. Negative differences were noted...
in southeast Africa, southern India, the east and west coasts of Australia, and the Amazon along the equator.

The integrated tropical ocean differences associated with the ENSO event vary between TRMM, GPCP, and other estimates and emphasize the need for additional validation and analysis to define the relations between precipitation anomalies and Pacific Ocean ENSO temperature changes.

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