

## Validation of TRMM and Other Rainfall Estimates with a High-Density Gauge Dataset for West Africa. Part II: Validation of TRMM Rainfall Products

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### ABSTRACT

Gauge data from a West African network of 920 stations are used to assess Tropical Rainfall Measuring Mission (TRMM) satellite and blended rainfall products for 1998. In this study, mean fields, scattergrams, and latitudinal transects for the months of May–September and for the 5-month season are presented. Error statistics are also calculated. This study demonstrates that both the TRMM-adjusted Geostationary Observational Environmental Satellite precipitation index (AGPI) and TRMM-merged rainfall products show excellent agreement with gauge data over West Africa on monthly-to-seasonal timescales and  $2.5^{\circ} \times 2.5^{\circ}$  latitude/longitude space scales. The root-mean-square error of both is on the order of  $0.6 \text{ mm day}^{-1}$  at seasonal resolution and  $1 \text{ mm day}^{-1}$  at monthly resolution. The bias of the AGPI is only  $0.2 \text{ mm day}^{-1}$ , whereas the TRMM-merged product shows no bias over West Africa. Performance at  $1.0^{\circ} \times 1.0^{\circ}$  latitude/longitude resolution is also excellent at the seasonal scale and good for the monthly scale. A comparison with standard rainfall products that predate TRMM shows that AGPI and the TRMM-merged product perform as well as, or better than, those products. The AGPI shows marked improvement when compared with the GPI, in reducing the bias and in the scatter of the estimates. The TRMM satellite-only products from the precipitation radar and the TRMM Microwave Imager do not perform well over West Africa. Both tend to overestimate gauge measurements.

### 1. Introduction

This article is the second of two articles that describe a joint Africa–U.S. project to validate satellite rain estimates and other rainfall products by using a high-resolution gauge dataset for West Africa. The gauge data were assembled as a workshop, held at The Florida State University, which included representatives of 11 West African nations. Data were obtained for over 1000 gaug-

es, roughly 10 times the number that are available in standard archives such as the Global Precipitation Climatology Project (GPCP) or the National Climatic Data Center dataset. These data have demonstrated both the quantity and quality of West African climate data available for research purposes.

The state-of-the-art global precipitation estimates are those of the GPCP (Huffman et al. 1997). GPCP produces a blended product in which Special Sensor Microwave Imager (SSM/I) observations are used to adjust rainfall estimates from infrared (IR) measurements on geostationary satellites (geo-IR). The adjusted estimates are further combined with gauge data to produce the GPCP, version 1, blended product. The Global Precipitation Climatology Center (GPCC) in Offenbach, Ger-

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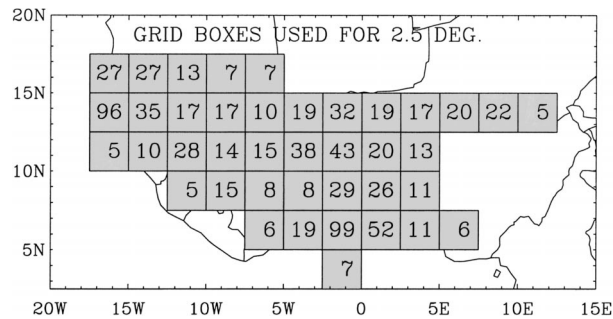


FIG. 1. Grid boxes with adequate gauge data for select satellite-gauge comparisons. Light shading indicates  $2.5^{\circ} \times 2.5^{\circ}$  boxes with five or more gauges; number of gauges in each box is indicated.

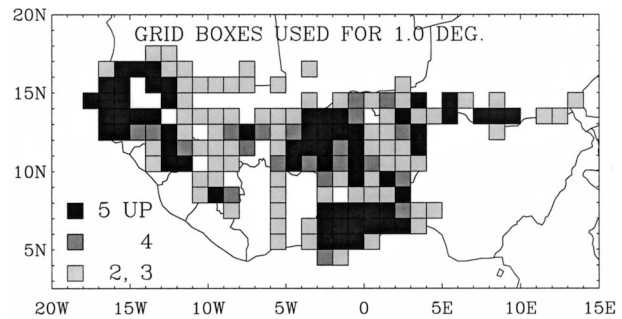


FIG. 2. Grid boxes with adequate gauge data for select satellite-gauge comparisons:  $1^{\circ} \times 1^{\circ}$  grid boxes with five or more gauges (dark shading), four gauges (medium shading), and two or three gauges per grid box (light shading).

many, provides the gauge data used for this product (Rudolf et al. 1994), but over Africa the sampling is very limited spatially and reporting is erratic in time. Neither the GPCP, version 1, product nor the GPCC gauge analysis had been validated over Africa.

In Nicholson et al. (2003, hereinafter Part I), we used the high-resolution gauge dataset assembled at the workshop to validate both the GPCP and the GPCC gauge analyses for 1998. A multiyear validation was also conducted using an archive with fewer stations than the workshop provided but far more than are available in the GPCC archive. Similar validation was done for the infrared-based Geostationary Operational Environmental Satellite precipitation index (GPI; Arkin and Meisner 1987) and the microwave-based product derived from the SSM/I (Ferraro 1997).

Although Tropical Rainfall Measuring Mission (TRMM) precipitation products have been extensively validated at ground sites around the world, none of these sites lies in Africa. The closest is in Israel, where the Mediterranean climate contrasts strongly with the climates over roughly 95% of Africa. In fact, the physical-dynamical processes that produce precipitation over most of Africa are considerably different than those that prevail at any of the ground validation sites. Thus, a specific validation for Africa is needed to ensure confidence in the TRMM estimates for this region. Here, in this article, such validation is done by comparing the workshop gauge data with five TRMM rainfall products. Because of the time lag caused by data assemblage and quality control in the national meteorological services, at the time of the workshop rainfall data were available only for 1998. Hence, the validation is limited to this year.

## 2. Data and method

### a. Gauge data

Detailed information on the workshop, the thereby-acquired gauge dataset, and data processing is presented in Part I. The workshop gauge dataset is used as a reference in estimating the error in the rainfall estimates

from various TRMM products. It is acknowledged that both gauge- and satellite-based estimates have nonnegligible errors (Morrissey and Greene 1993; Sevruk 1982; Legates and Willmott 1990; Rudolf et al. 1994; Morrissey et al. 1995; Huffman et al. 1995, 1997). Xie and Arkin (1995), however, concluded that the random errors in the gauge data are small when compared with the bias in satellite estimates, if an adequate number of gauges is used. Their results suggested that when five or more gauges are available in a  $2.5^{\circ} \times 2.5^{\circ}$  latitude/longitude grid box, the error of the areal averages from the gauges is about 10% or less.

Using that as a criterion for validation, we have identified 40  $2.5^{\circ} \times 2.5^{\circ}$  grid boxes with five or more reference gauges. Figure 1 shows these, together with the total number of gauges in each grid. Most grid boxes contain 10–50 gauges, and some contain over 90 stations, so that an excellent spatial average could be produced. This permits us to make the assumption that the bias in the spatial averages of gauge data is relatively small, allowing the bias and random error of the satellite-based rainfall estimates to be adequately approximated. This assumption is further justified in Part I.

To grid the data, a straightforward arithmetic average of all stations in each grid box was used. Then two initial approaches to contouring of precipitation fields were considered, fast Fourier transform (FFT; NCAR 1993) and a “nearest neighbor” method. The former utilizes a curve-fitting program based on FFTs. The latter interprets a grid box’s value based on a weighted sum of values at local, neighboring points. We tested the sensitivity of the analysis to the method chosen by producing latitudinal transects for a 7-yr period with low station density and comparing these with a transect of the long-term mean derived from a far greater number of stations. The transects derived from the FFT routine and the nearest-neighbor method were very similar. However, in both cases, there were problems at the boundaries and in areas of very high gradients. In general, the differences were relatively small except in areas where the station network is very sparse (or at the boundaries). The comparison with the long-term mean

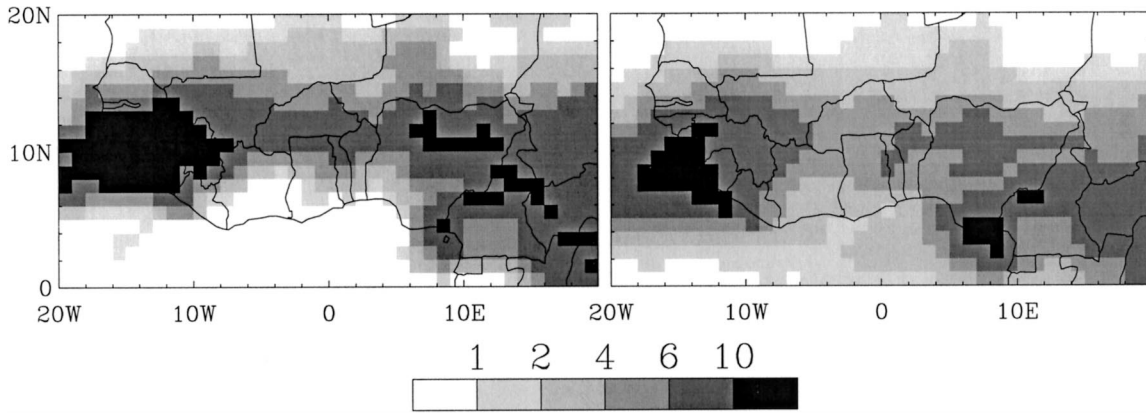


FIG. 3. Rainfall in (left) Aug 1998 and (right) for the May–Sep season of 1998, based on finescale ( $1^\circ \times 1^\circ$ ) AGPI data.

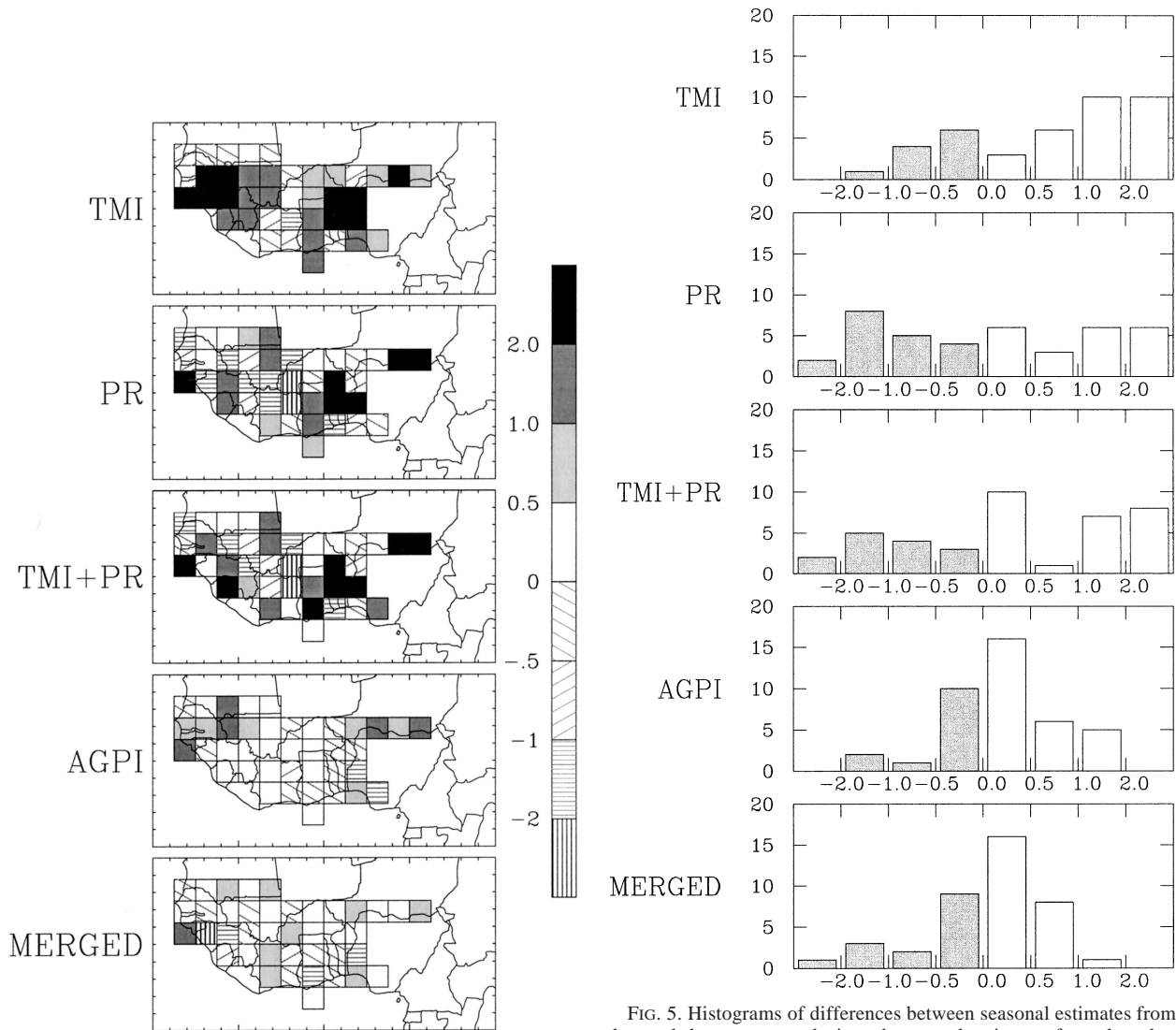


FIG. 4. Difference fields ( $\text{mm day}^{-1}$ ) between the workshop gauge analysis for the season and the five TRMM rainfall products.

FIG. 5. Histograms of differences between seasonal estimates from the workshop gauge analysis and seasonal estimates from the other rainfall products ( $\text{mm day}^{-1}$ ). Positive values indicate overestimation by the other rainfall products.

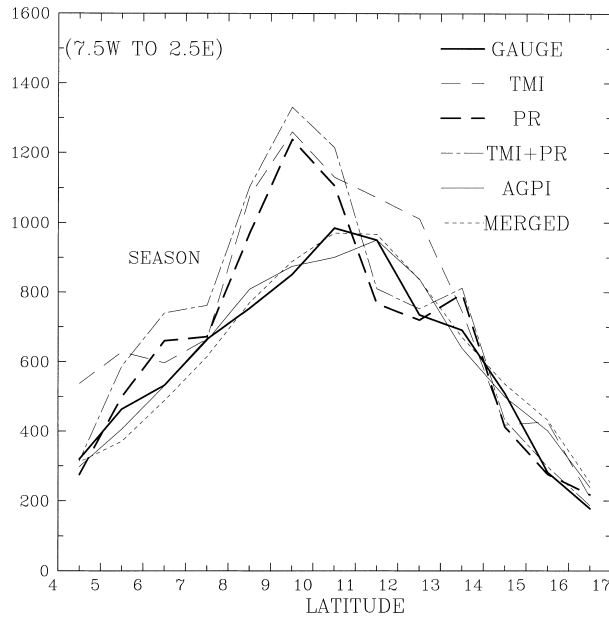


FIG. 6. Meridional transects of seasonal rainfall averaged for the region from 7.5°W to 2.5°E (based on  $1^\circ \times 1^\circ$  data).

suggested that the nearest-neighbor method is more suitable over Africa, and, hence, this method was selected.

#### b. TRMM rainfall estimates

Details of the TRMM mission and instruments on the satellite can be found in Kummerow et al. (2000). TRMM, despite its state-of-the-art instruments and extensive validation, is limited in its temporal sampling. For that reason, an approach taken by Adler et al. (2000) and others is to use TRMM as a “flying rain gauge” and to create blended products that extend the accuracy of TRMM to time and space resolutions that are not available from TRMM alone. The basic TRMM sensors are a passive microwave radiometer [the TRMM Microwave Imager (TMI)], a microwave radar unit [precipitation radar (PR)], and a visible and infrared radiometer [visible and infrared scanner (VIRS)]. These are variously combined with other IR and gauge-based products. The use of IR for precipitation estimation is based on an association between cloud-top temperature and intensity of convection. The physical connection between the IR radiances and surface precipitation is relatively weak, as compared with the TRMM passive and active microwave sensors. However, IR estimates from geo-IR provide considerably better time/space coverage than the TRMM satellite.

The TRMM products used here for comparison with the reference gauge dataset include the TMI product (2A12), the TRMM PR (2A25), the TRMM-adjusted GPI (AGPI; 3B42), the TMI + TRMM PR combined product (2B31), and the TRMM merged analysis (3B43). The derivation of the blended products is de-

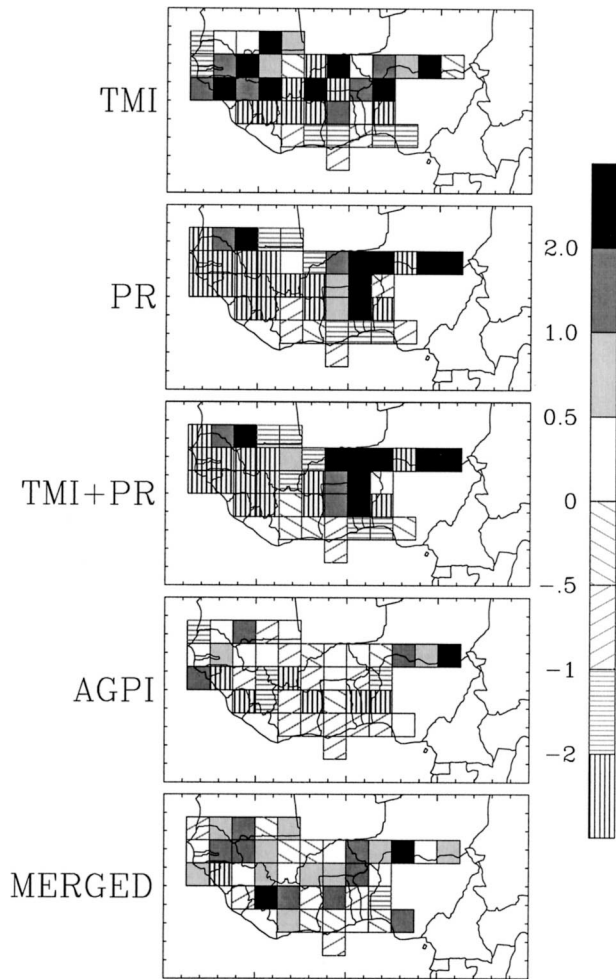


FIG. 7. Difference fields ( $\text{mm day}^{-1}$ ) between the workshop gauge analysis for Aug and the five TRMM rainfall products for Aug.

scribed by Adler et al. (2000). The AGPI is justified by the studies of Adler et al. (1993, 1994) that show that biases in the GPI, which assigns a single rain rate to all pixels colder than a specified temperature threshold, can be minimized by appropriately adjusting the GPI rain rate in time and space. The TRMM AGPI is produced by first using the TRMM combined instrument (TCI; a combined algorithm using both PR and TMI) data plus the VIRS data to produce a time- and space-varying IR–rain-rate relationship that matches the TCI-inferred rain rate (Adler et al. 2000). This adjusted IR–rain-rate relationship is then applied to the geo-IR data with better time sampling.

A final blended product, the “TRMM and other data merged estimate” (TRMM merged) is derived by combining the AGPI with rain gauge information from the GPCP gauge analysis (Rudolf 1993). The two-step procedure of Huffman et al. (1997) is used, in which the AGPI value for each grid box is adjusted using a gauge average for the box; then, the AGPI and gauge value

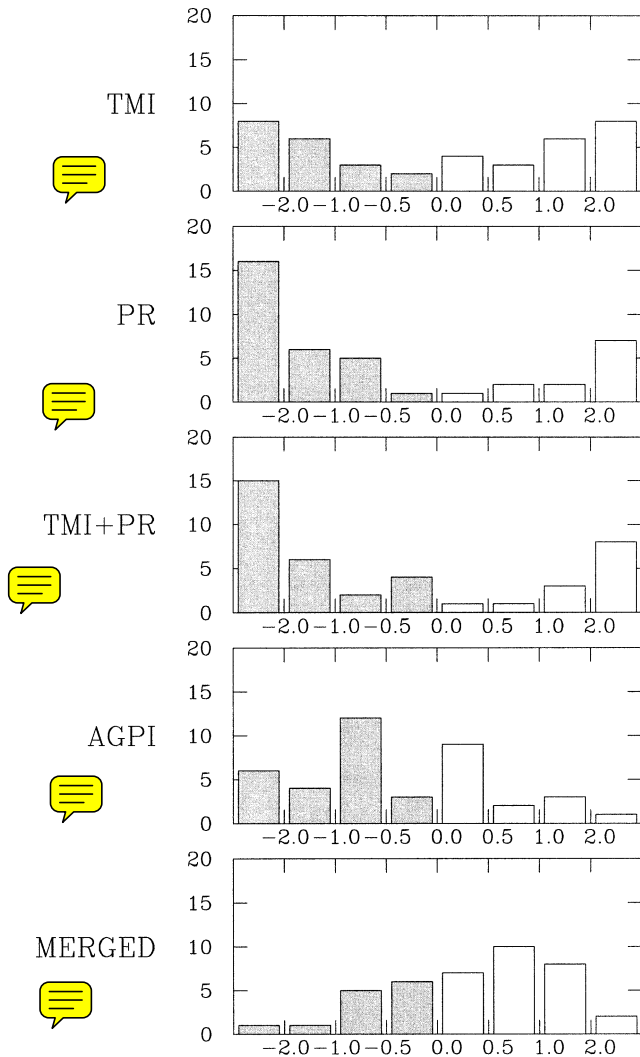


FIG. 8. Histograms of differences between Aug estimates from the workshop gauge analysis and estimates from the other rainfall products ( $\text{mm day}^{-1}$ ). Positive values indicate overestimation by the other rainfall products.

are combined, using a weighting factor inversely proportional to the error of the two products. Here, the gauge data used as a reference are almost independent of that in the GPCC analysis, because the number of stations in the former (roughly 920) is so much larger than the number in the latter (roughly 75). Furthermore, many of the gauges used for the GPCC analysis did not report every day of the month. Therefore, the gauge dataset assembled at the workshop provided a nearly independent validation of the TRMM-merged product.

The TRMM rainfall products evaluated here cannot be expected to provide results that are identical to the gauge estimates because of differences in temporal and spatial sampling. The most obvious contrasts are that gauges give point measurements while satellites produce spatial averages and that TRMM actually “sees” each

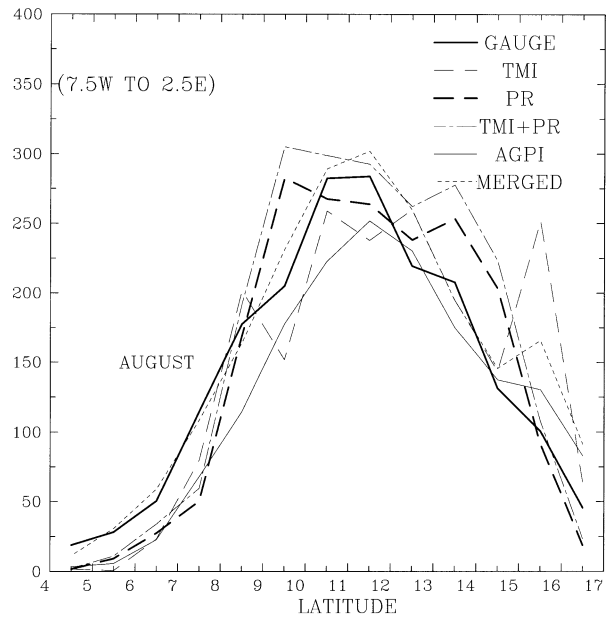


FIG. 9. Meridional transects of Aug rainfall averaged for the region from 7.5°W to 2.5°E (based on  $1^\circ \times 1^\circ$  data).

site for only a limited period of time. The time is so brief that TRMM alone cannot establish the diurnal cycle. These sampling issues are beyond the scope of this work, which takes an operational perspective. We are merely answering the question, “Will product X give me a reasonably good picture of the rainfall field over West Africa, as assessed from gauge data?”

### 3. Data processing and analysis

Validation was limited to the rainy-season months of May–September, because of limited data availability in the remaining months. Two kinds of validation exercises were carried out. In the first, the mean rainfall fields for August and for the 5-month season were compared for various TRMM products. August was selected as an example at the monthly scale, because it is the wettest month throughout most of the analysis region. The results are presented as difference maps and latitudinal transects. The latter, averaged over  $10^\circ$  of longitude and centered on  $2.5^\circ\text{W}$ , facilitated the comparison of gradients and magnitudes in the products. For these, the number of required gauges per grid was reduced to three to provide an increased spatial coverage. A test of the influence of station number on grid average showed that, in most cases, the average based on three randomly chosen stations in the grid was not greatly different from that based on all stations in the grid.

The second exercise was calculation of error statistics for each month from May to September and for the 5-month season. Bias, root-mean-square error, and ratios are derived using the workshop gauge dataset as a reference. The bias is calculated as the difference between

the satellite mean and the gauge mean, and the rms error is calculated after the bias is removed from the satellite estimate. This analysis includes scattergrams of the gauge data versus the other products, which are presented in section 4b. These graphically depict the degree of error, which is quantified in section 4c. For the error analysis (including the scattergrams), only those grid boxes with five or more gauges were considered. Both exercises were also carried out using  $63\ 1^\circ \times 1^\circ$  grid boxes, but only for the TRMM AGPI and the merged product. Those grid boxes are shown in Fig. 2.

An initial comparison between the gauge data and the AGPI data showed, in general, superb agreement but with a few extreme outliers. To determine whether the gauge data might be in error, the stations in the grids represented by the outliers were examined to determine the “problem” stations. This analysis suggested that the gauge data are good, because all of these stations (13 in Guinea and 5 in Sierra Leone) were located along the coast where there is a strong degree of rainfall enhancement by coastal effects. In some cases, rainfall exceeded  $1000\ \text{mm month}^{-1}$ . It appears that TRMM could not capture the coastal effect, perhaps because of the intense rainfall from warm, stratiform clouds or a preset threshold to discard “ambiguous” data. Also, these grid boxes that contain these stations partially included the ocean, where no gauges existed to produce a truly representative grid average. To provide a more representative picture of the accuracy of TRMM, the two grid boxes containing these 18 stations were removed from the analyses.

#### 4. Results: Spatial fields of seasonal and August rainfall

Figure 3 shows the mean rainfall in millimeters per day over West Africa during August and during the May–September season of 1998. This is based on the finescale  $1^\circ \times 1^\circ$  AGPI data. AGPI is used to depict the rainbelt because it provides more extensive spatial coverage than gauge data and, as will be shown later, it provides an excellent estimate of season totals.

The central core of the rainbelt is evident in the latitudes of roughly  $6^\circ$ – $14^\circ\text{N}$ . In this core, rainfall generally exceeds  $4\ \text{mm day}^{-1}$ , or roughly  $120\ \text{mm month}^{-1}$ . The enhancement of rainfall by local topographic features is also strongly apparent, particularly in the highlands of Guinea ( $\sim 10^\circ\text{N}$ ,  $12^\circ\text{W}$ ), northern Nigeria ( $\sim 12^\circ\text{N}$ ,  $10^\circ\text{E}$ ), and Cameroon ( $\sim 6^\circ\text{N}$ ,  $10^\circ\text{E}$ ). This map serves as a point of comparison for the TRMM product–gauge difference fields.

##### a. Mean seasonal rainfall

Figure 4 presents the difference fields for the five TRMM products minus gauge estimates for the May–September season. To facilitate a comparison of the performance of the various products, histograms showing

the number of grids in various difference categories are presented in Fig. 5. Both figures clearly show that for the pure TRMM products, TMI, PR, and TMI + PR combined, the differences between satellite and gauge are considerably larger than for AGPI and TRMM-merged products. For the PR and the TMI + PR combined, the differences appear to be random, with many grid boxes indicating overestimation and many indicating underestimation. The TMI appears to overestimate seasonal rainfall. For both the PR and TMI, there are only 19 of 40 grid boxes for which the differences are less than  $1\ \text{mm day}^{-1}$ , and these are mostly in the north (where mean daily rainfall is generally less than  $6\ \text{mm day}^{-1}$ ). The combined product does somewhat better, although differences are less than  $1\ \text{mm day}^{-1}$  in only 18 grid boxes, more cases fall within  $\pm 0.5\ \text{mm day}^{-1}$  of the gauge analysis.

In contrast, the satellite–gauge differences for the AGPI and TRMM-merged products are considerably smaller and appear to be very random. For the AGPI product, they exceed  $0.5\ \text{mm day}^{-1}$  in only 14 of the 40 grid boxes and exceed  $1.0\ \text{mm day}^{-1}$  in only 7 grid boxes. For the TRMM-merged product, they exceed  $0.5\ \text{mm day}^{-1}$  in only 15 of the 40 grid boxes and exceed  $1.0\ \text{mm day}^{-1}$  in only 5 grid boxes. The histograms clearly show the concentration of grid boxes with differences of less than  $0.5\ \text{mm day}^{-1}$ .

Meridional transects of seasonal rainfall during 1998 were calculated for a  $10^\circ$  longitude band from  $2.5^\circ\text{E}$  to  $7.5^\circ\text{W}$ , using for each dataset the grid boxes or stations within this area. In Fig. 6, a comparison is made between a transect based on the workshop gauges and the TRMM satellite products. There is remarkably good agreement between the AGPI, TRMM-merged, and gauge data at the seasonal scale at all latitudes. Farther north, TRMM appears to overestimate rainfall by 50–100 mm. The PR, TMI, and TMI + PR all show a similar pattern, with a core of the rainbelt that is 40% more intense and is shifted  $1^\circ$ – $2^\circ$  southward of that indicated by the gauge data.

##### b. Performance of the TRMM products at monthly resolution

Figure 7 shows satellite–gauge difference fields for the month of August, and Fig. 8 presents histograms of these differences. August is selected for detailed analysis because it is the rainiest month over most of the analysis sector, providing about 30%–40% of the annual rainfall in areas near  $12^\circ\text{N}$ , but 50% or more in areas near  $18^\circ\text{N}$ . Figures 7 and 8 can be compared with the seasonal differences in Figs. 4 and 5. For the PR and the TMI + PR combined, there appears to be more random error during August than for the season as a whole. For both products, differences exceed  $2\ \text{mm day}^{-1}$  in more than one-half of the grid boxes, and both clearly underestimate rainfall, especially in the western sectors. For the TMI, the differences appear

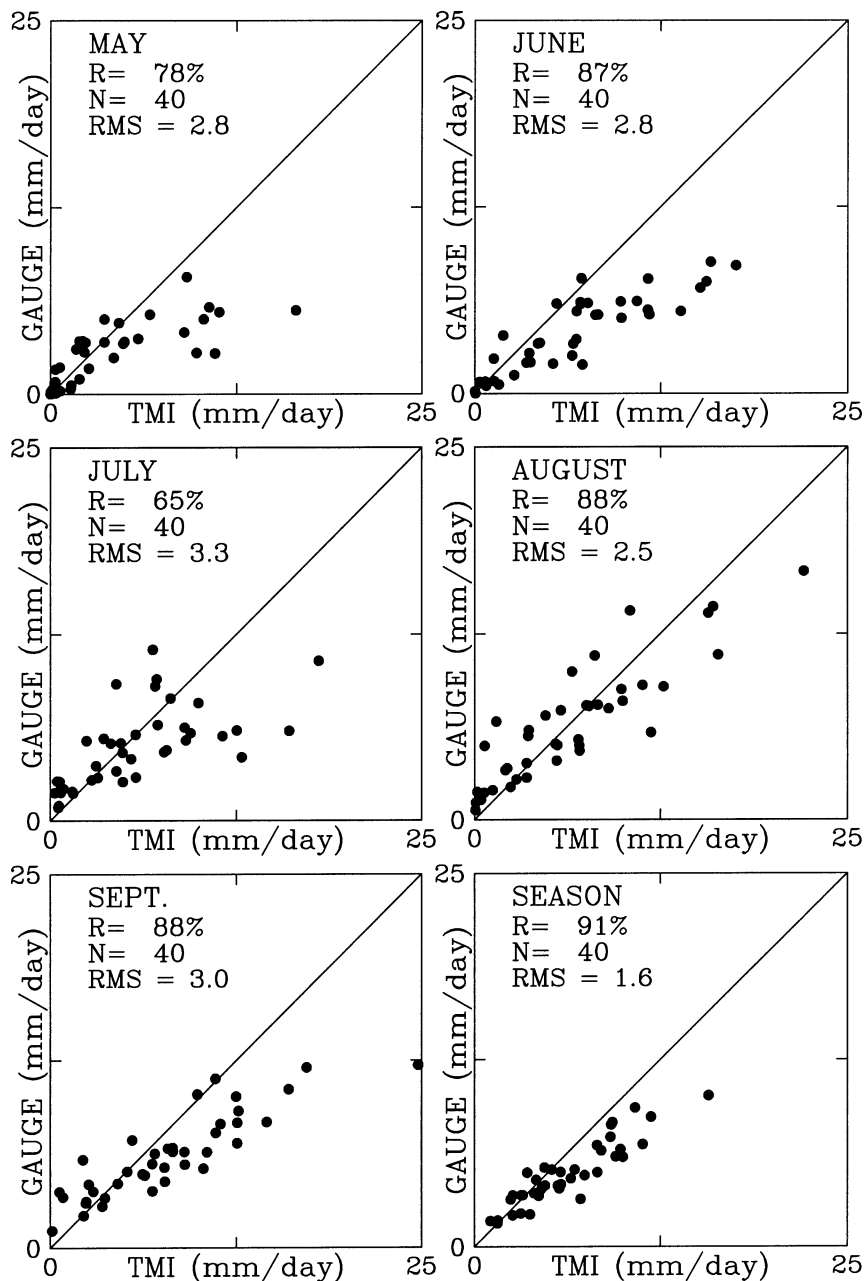


FIG. 10. Scattergrams of the workshop gauge analysis vs TMI ( $\text{mm day}^{-1}$ ) for each month for May–Sep plus the 5-month season (based on  $2.5^\circ \times 2.5^\circ$  data). Correlation, number of correlation pairs, and rms error are indicated.

to be both smaller and somewhat random. They exceed  $1 \text{ mm day}^{-1}$  in most grid boxes and  $2 \text{ mm day}^{-1}$  in 16 of the 40 grid boxes. There is some tendency for underestimation in the south and overestimation in the north.

The AGPI and TRMM-merged products perform notably better than the three TRMM-only products. The AGPI–gauge differences exceed  $1 \text{ mm day}^{-1}$  in only 14 grid boxes, and the TRMM-merged product–gauge differences exceed this in only 12 grid boxes. There is a

tendency for the TRMM-merged product to overestimate August rainfall and for AGPI to underestimate it.

Figure 9 shows rainfall as a function of latitude during August of 1998. As is the case for the season as a whole (Fig. 6), the core of the rainbelt is at roughly  $10^\circ\text{--}12^\circ\text{N}$  and peak rainfall is on the order of  $300 \text{ mm month}^{-1}$ . This analysis tends to confirm the trends seen in Figs. 7 and 8. There is exceedingly good agreement with the TRMM-merged product, but AGPI tends to underestimate rainfall at most locations. TMI generally under-

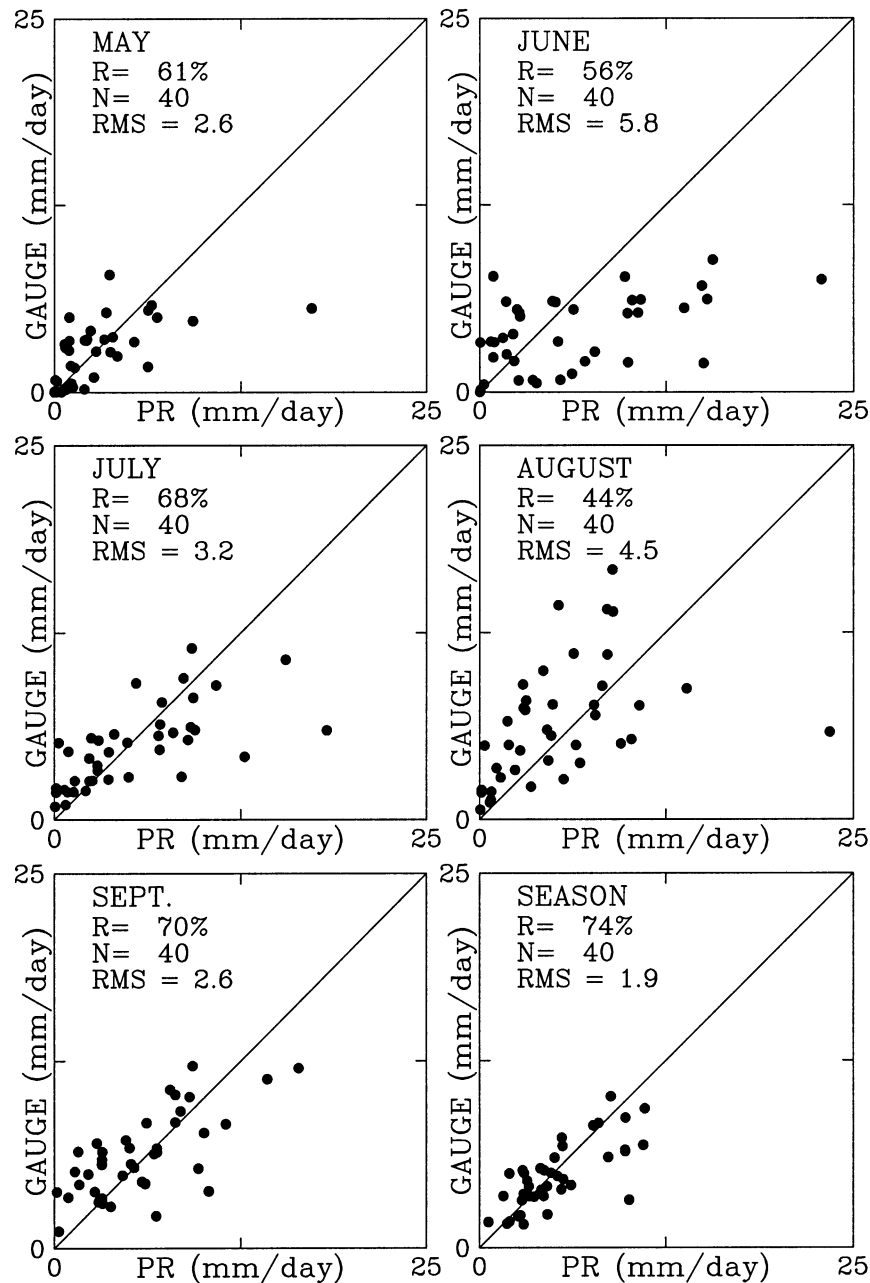


FIG. 11. Scattergrams of the workshop gauge analysis vs PR ( $\text{mm day}^{-1}$ ) for each month for May–Sep plus the 5-month season. Otherwise, as in Fig. 10.

estimates rainfall in the south and overestimates in the north. AGPI and TRMM-merged products also show some degree of overestimation in areas to the north of the rainbelt. The PR and TMI + PR combined products indicate a rainbelt that is too broad, with sharp gradients north and south of it.

Figures 10–14 show scattergrams that compare TRMM products with gauge data at the  $2.5^\circ$  scale. The blended products clearly outperform the three pure TRMM products. Of the three, the best performance is

that of the TMI (Fig. 10). Correlations with the gauge analysis range from 0.65 in July to 0.88 in August and September, and the correlation for the season is 0.91. Rms error ranges from 2.5 in August to 3.3 in July but is only  $1.6 \text{ mm day}^{-1}$  for the season. The performances of PR and TMI + PR combined are very similar (Figs. 11 and 12). Correlations range from 0.44 to 0.76 for individual months and are 0.74 and 0.78 for the season for PR and TMI + PR, respectively. The rms error is as high as  $6 \text{ mm day}^{-1}$  in June but is generally 2.7–4.5 for

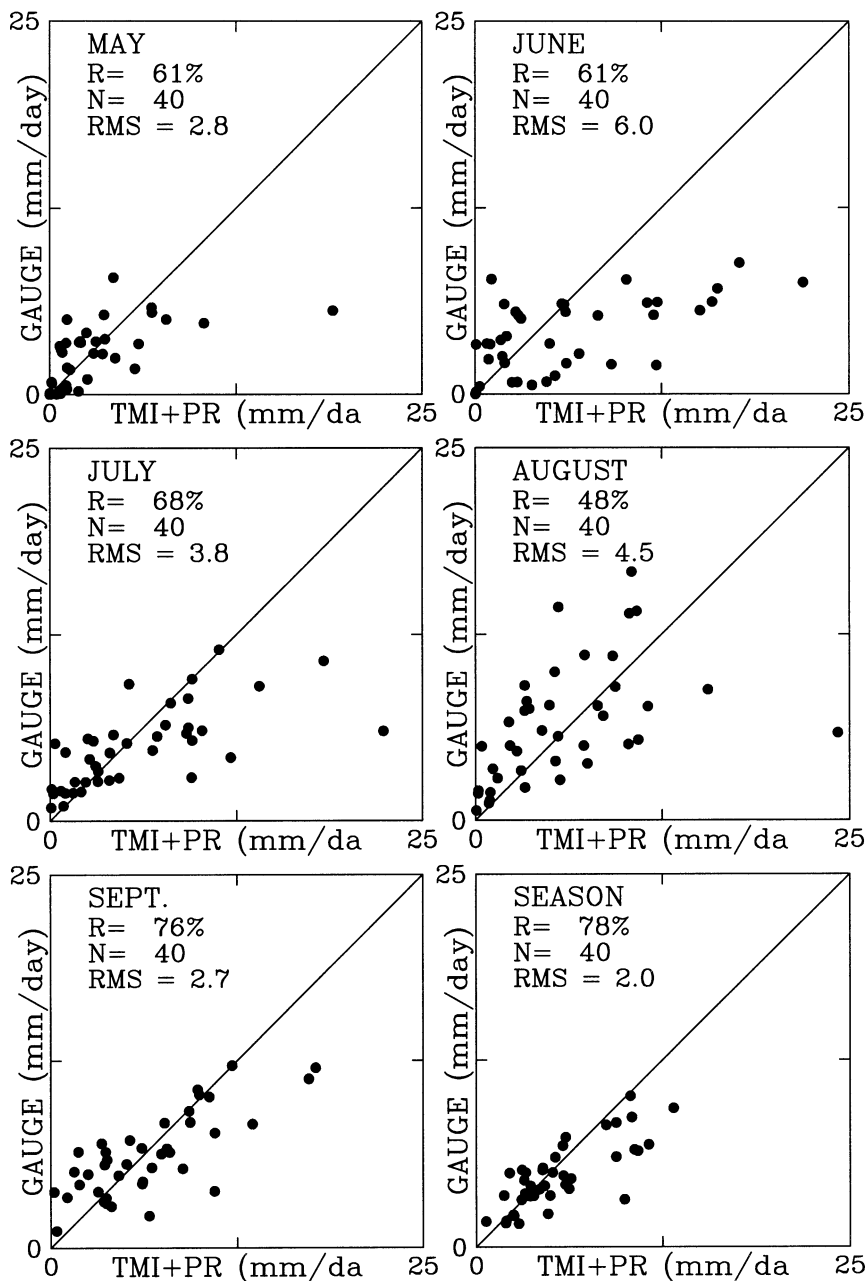


FIG. 12. Scattergrams of the workshop gauge analysis vs TMI + PR ( $\text{mm day}^{-1}$ ) for the months May–Sep and the 5-month season. Otherwise, as in Fig. 10.

the other months and is on the order of  $2.0 \text{ mm day}^{-1}$  for the season.

In contrast, the two blended products perform exceedingly well at the monthly scale. For both the AGPI (Fig. 13) and TRMM-merged (Fig. 14) products, correlations exceed 0.92 in three of the five months and the correlation for the season as a whole is 0.95 for both products. Overall, the performance of the TRMM-merged product is very similar to that of the AGPI, except during July.

*c. Error statistics*

Error statistics (Fig. 15) are calculated by comparing rainfall estimates at individual grid boxes with gauge averages for the 40 grid boxes shown in Fig. 4. Additive bias, percent additive bias, and bias-corrected rms error are calculated for each month from May to September and for the 5-month season as a whole.

The results underscore the poor performance of the pure TRMM products and the good performance of the

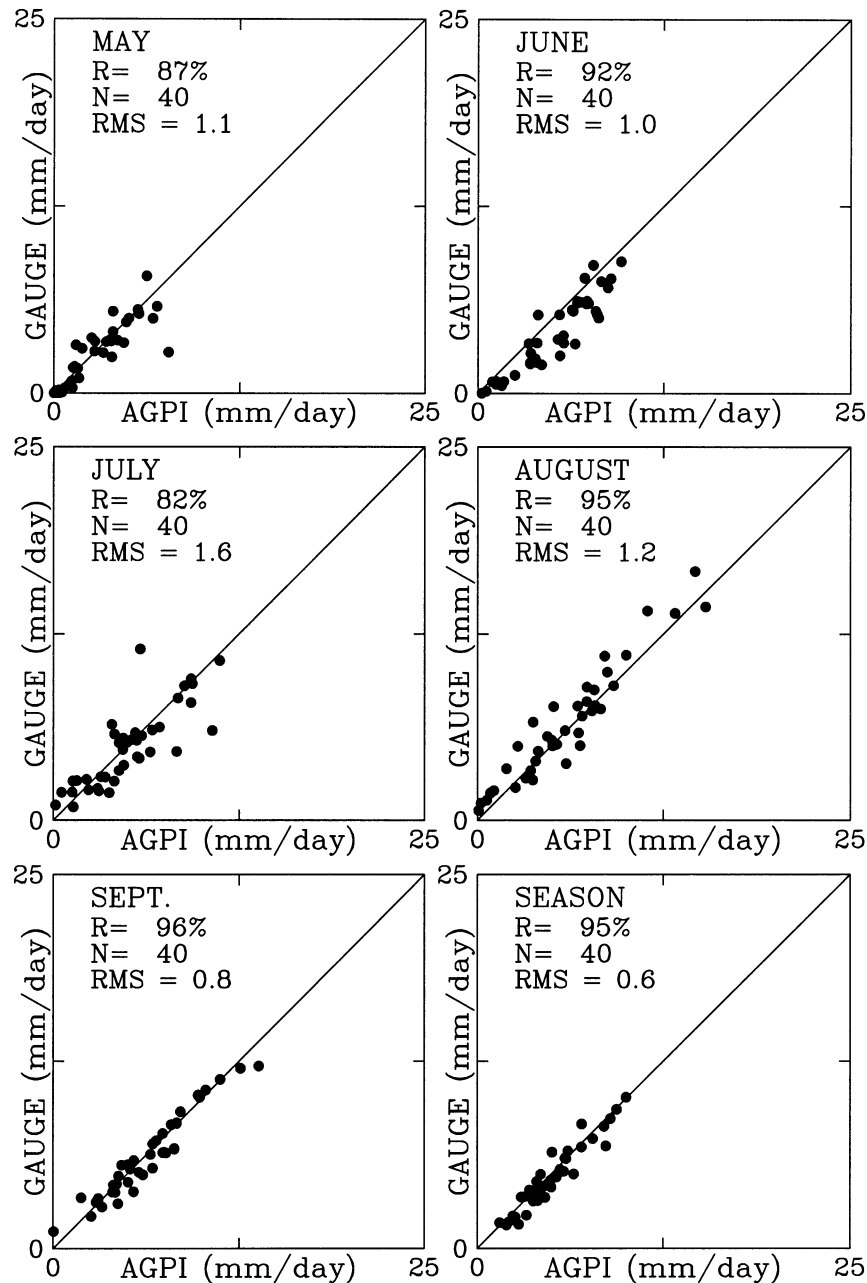


FIG. 13. Scattergrams of the workshop gauge analysis vs AGPI ( $\text{mm day}^{-1}$ ) for each month for May–Sep plus the 5-month season. Otherwise, as in Fig. 10.

blended products. As noted earlier, the TMI performs better than the PR, a fact that might be explained by the better sampling of the TMI. With the exception of June, the bias is much less than  $1 \text{ mm day}^{-1}$  for AGPI and TRMM-merged products, or generally less than 5%. The rms error is on the order of  $1 \text{ mm day}^{-1}$  for both and is much less for the season as a whole. For TMI and PR, the bias is on the order of  $1\text{--}2 \text{ mm day}^{-1}$  (except in June). It is positive for the TMI in all months, indicating that the TMI overestimates rainfall over Africa. The bias of the PR is positive in three of five cases but

is near zero for the season as a whole. The percent bias is variable and ranges from near zero for TMI in August to roughly 70% in June. The rms error of TMI and PR ranges from about 2 to  $6 \text{ mm day}^{-1}$ . In all cases, the error and bias of the TMI + PR is almost the same as that of the PR alone.

Table 1 summarizes the error statistics and compares them with the statistics for the pre-TRMM estimates discussed in Part I. For the season, the rms error is 0.6 and  $0.7 \text{ mm day}^{-1}$ , respectively, for the AGPI and TRMM-merged products at  $2.5^\circ$  resolution. This is com-

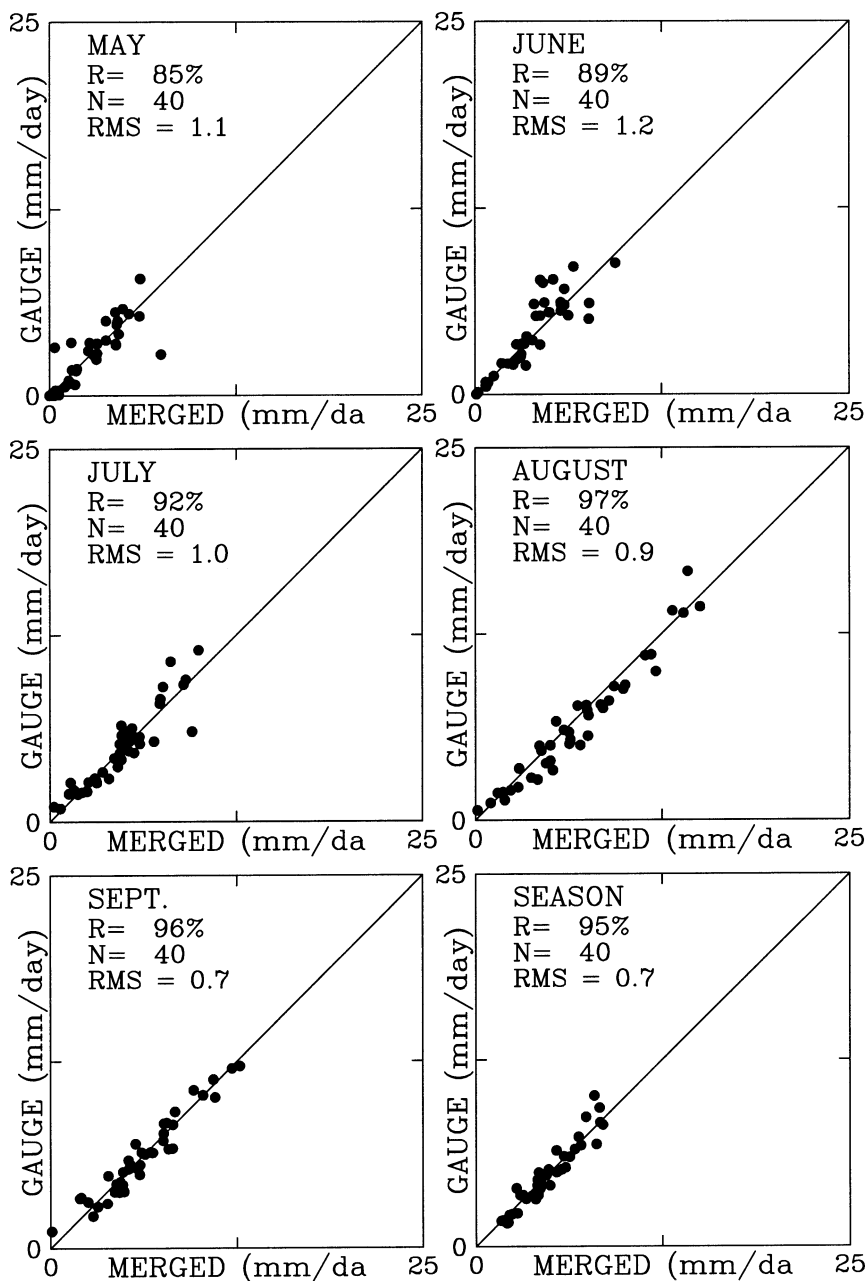


FIG. 14. Scattergrams of the workshop gauge analysis vs TRMM-merged product (mm day<sup>-1</sup>) for each month for May–Sep plus the 5-month season. Otherwise, as in Fig. 10.

parable to the rms error for GPCP, version 1; GPI; and GPCC gauge data. The bias is 0.2 (4%) for the AGPI and 0 mm day<sup>-1</sup> for the TRMM-merged product at 2.5° resolution. This result is comparable to the bias of GPCP, version 1, and GPCC and is somewhat lower than the bias of the PR and the TMI + PR. The bias is several times as large for the TMI, GPI, and SSM/I.

For August, the statistics are considerably different. The rms error is 1.2 and 0.9 mm day<sup>-1</sup>, respectively, for AGPI and TRMM-merged products, and 2–4 times as large for TMI, PR, and TMI + PR. The August rms

errors for the AGPI and the TRMM-merged products are similar to that of the GPCP and the GPCC but are considerably lower than that for GPI or SSM/I.

In general, it appears that the pure TRMM products provide little improvement when compared with the pre-TRMM products. On the other hand, the TRMM AGPI and TRMM-merged products provide notable improvement. At the seasonal scale, the AGPI and TRMM-merged products have a bias-corrected rms error comparable to those of the GPCP, version 1, blended product, GPI, and GPCC gauge dataset, and they have con-

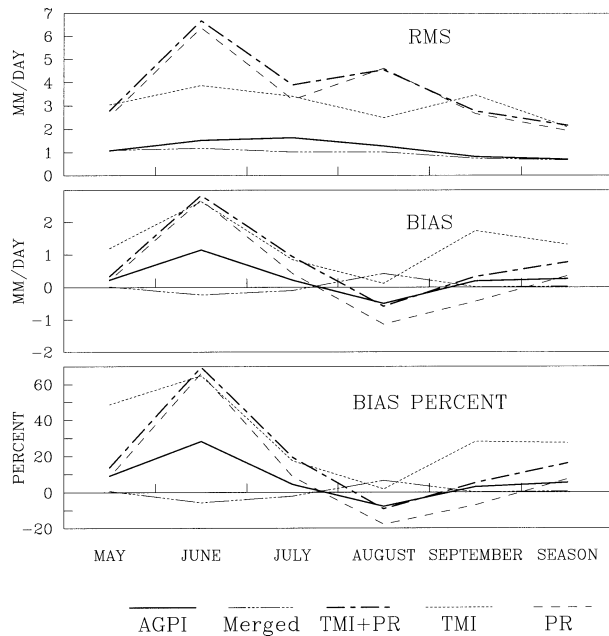


FIG. 15. Error analysis of the five TRMM products for each month and for the 5-month season: (top) rms error ( $\text{mm day}^{-1}$ ), (middle) additive bias ( $\text{mm day}^{-1}$ ), and (bottom) percent additive bias (%).

siderably lower bias than the GPI. On the monthly scale, the rms error is comparable to that of GPCP and GPCC but is considerably lower than that of GPI.

The error statistics also confirm a trend evident in the scattergrams: exceedingly poor performance of the pure TRMM products in June and lower performance of some other products in this month. A complete analysis of the reasons for this was not done. However, we hypothesize that the disparity between the TRMM products and the gauge data relates to atmospheric aerosols. Daily TOMS aerosol products for individual days in June and July indicated a general correspondence between the grid boxes with large errors in the PR and TMI and the grid boxes with dense aerosol outbreaks during the month. Rosenfeld (1999) has shown that the aerosols can significantly modify the droplet size distribution and cloud temperatures; thus, it is likely that the TMI product would be affected. An impact on the

PR is not so readily apparent, but an influence on the performance of the PR algorithm over Africa is none the less conceivable. In view of the high density of aerosols over West Africa throughout most of the year, an aerosol correction would likely improve the TRMM estimates.

#### d. Performance of the blended products at the finescale

The previous analyses show that the AGPI and TRMM-merged products both perform well at the  $2.5^\circ$  resolution. In view of this, it is meaningful to determine the quality of performance at the higher resolution of  $1^\circ \times 1^\circ$ . At this resolution, there are few grid boxes that meet the five-gauge criterion. However, the excellent performance of GPCP (Nicholson et al. 2001) and other results suggest that accurate estimates can be provided by fewer gauges. When the criterion is lowered to two gauges, 160 grid boxes can be used for comparing gauge and TRMM estimates.

Figure 16 shows the differences between AGPI and gauge data and between the TRMM-merged product and gauge data. Some degradation of performance is evident when compared with the  $2.5^\circ$  estimates, but the errors are still generally within  $1 \text{ mm day}^{-1}$  at the seasonal timescale. Errors are greater in the monthly (August) estimates but are still less than  $2 \text{ mm day}^{-1}$  in all but 33 grid boxes.

Scattergrams (Fig. 17) suggest that for August and for the season as a whole the performances of the TRMM-merged product and AGPI are roughly equal. Figure 18 shows the rms error, bias, and percent bias for all months. The rms error is somewhat higher in the wetter months of July–August but overall varies between only  $1$  and  $2 \text{ mm day}^{-1}$  for both the AGPI and TRMM-merged products. The bias varies somewhat more. It is largest in June for AGPI but is still just over  $1 \text{ mm day}^{-1}$ . In all other months and for the season, it is considerably smaller than  $1 \text{ mm day}^{-1}$  for both the AGPI and TRMM-merged products at the  $1^\circ \times 1^\circ$  level of resolution.

TABLE 1. Error statistics for various TRMM and pre-TRMM rainfall products: rms error, additive bias, percent additive bias on a seasonal basis, and rms error for Aug totals.

	Rms ( $\text{mm day}^{-1}$ ) Season	Bias ( $\text{mm day}^{-1}$ ) Season	Bias (%) Season	Rms ( $\text{mm day}^{-1}$ ) Aug
AGPI	0.6	0.2	4	1.2
TRMM merged	0.7	0.0	0	0.9
TMI	1.6	1.3	28	2.5
PR	1.9	0.3	7	4.5
TMI + PR	2.0	0.7	18	4.5
GPCP	0.6	0.1	3	1.0
GPCC	0.8	-0.2	-4	1.2
SSM/I	1.5	1.6	32	2.7
GPI	0.8	1.3	27	2.5

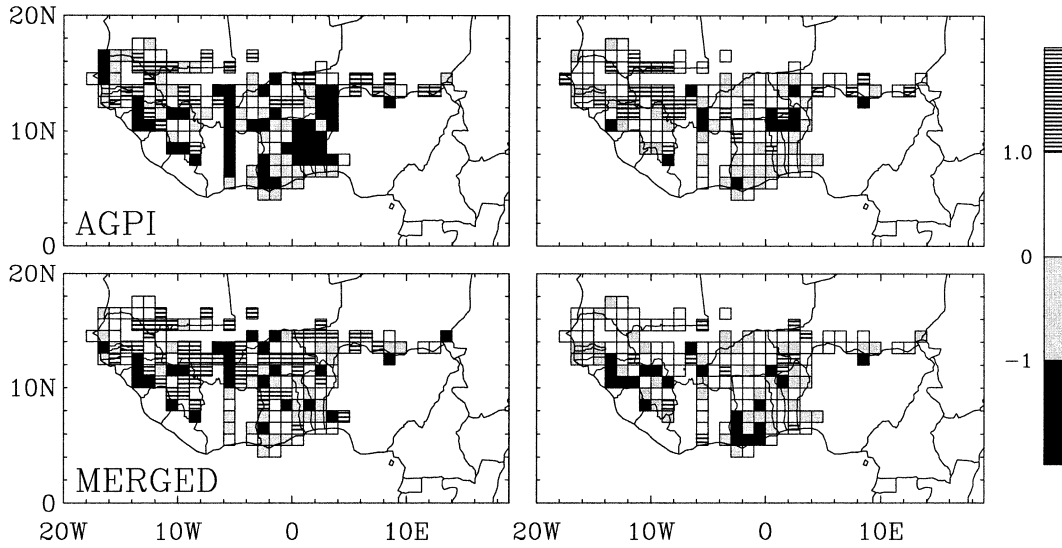


FIG. 16. Difference fields ( $\text{mm day}^{-1}$ ) between the workshop gauge analysis and the best-performing TRMM rainfall products (AGPI and TRMM merged) at the  $1^\circ \times 1^\circ$  level of resolution: (left) Aug and (right) seasonal differences.

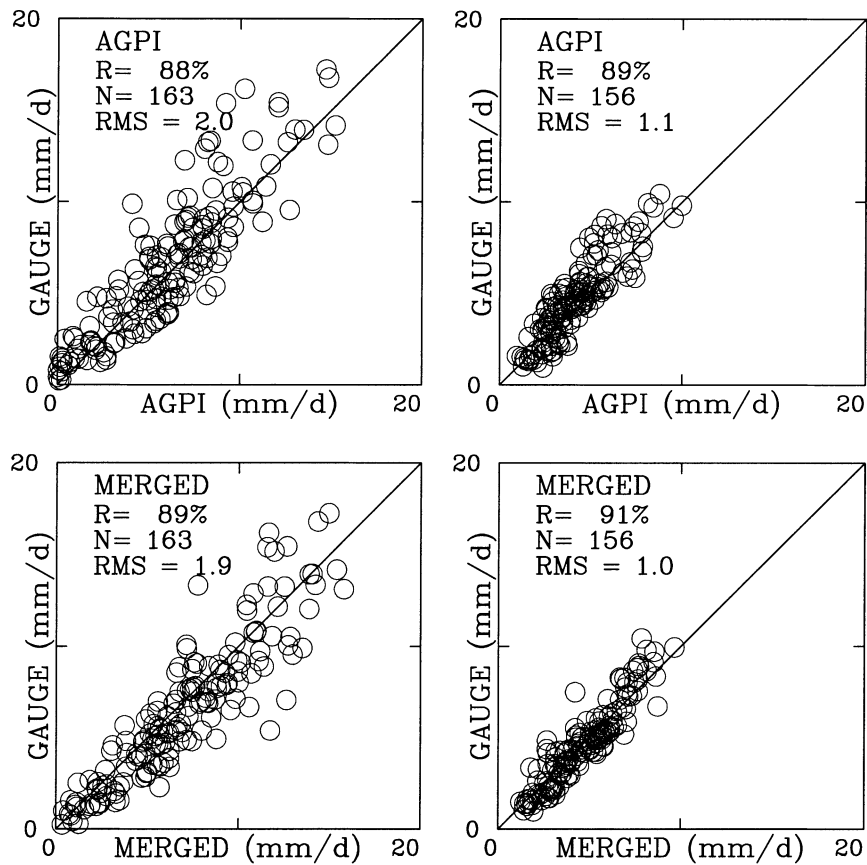


FIG. 17. Scattergrams of the workshop gauge analysis vs AGPI and the TRMM-merged product ( $\text{mm day}^{-1}$ ) for (left) Aug and (right) the 5-month season at the  $1^\circ \times 1^\circ$  level of resolution.

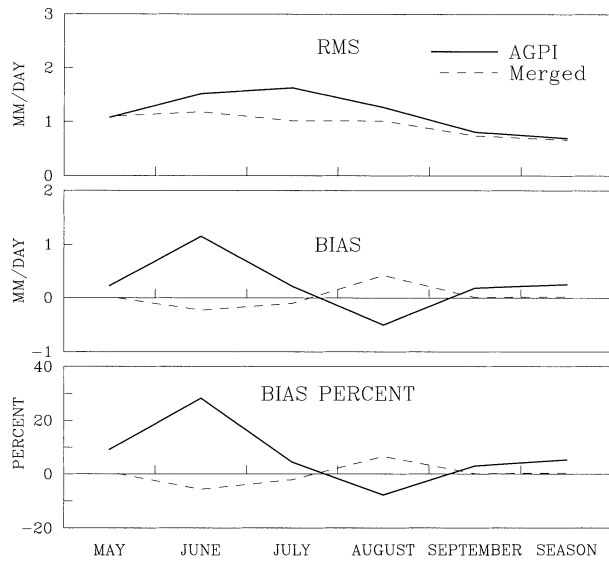


FIG. 18. Error statistics for the AGPI and TRMM-merged products at the  $1^\circ \times 1^\circ$  level of resolution for each month and for the 5-month season: (top) rms error ( $\text{mm day}^{-1}$ ), (middle) additive bias ( $\text{mm day}^{-1}$ ), and (bottom) percent additive bias (%).

## 5. Summary and conclusions

This preliminary analysis has demonstrated that both the TRMM-adjusted GPI and TRMM-merged rainfall products show excellent agreement with gauge data over West Africa on monthly-to-seasonal timescales and  $2.5^\circ \times 2.5^\circ$  latitude/longitude space scales. The rms error of both products is on the order of  $0.6 \text{ mm day}^{-1}$  at seasonal resolution but is typically about  $1 \text{ mm day}^{-1}$  at monthly resolution. The bias of the AGPI is only  $0.2 \text{ mm day}^{-1}$ , whereas the TRMM-merged product shows no bias over West Africa. The AGPI has shown marked improvement, when compared with the GPI, in reducing both the bias and the scatter of the estimates. Neither the TMI nor the PR performs well over West Africa. The TMI shows some tendency to overestimate gauge measurements. Both the bias and the rms error are high. The PR also has a net tendency to overestimate the gauge data, but the errors appear to be more random than systematic.

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