NOTES AND CORRESPONDENCE

Evaluation of the Research-Version TMPA Rainfall Estimate at Its Finest Spatial and Temporal Scales over the Rome Metropolitan Area

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ABSTRACT

The focus of this study is the evaluation of the research-version Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) rainfall product at its finest spatial and temporal resolutions (3-hourly and 0.25° × 0.25°) over the Rome, Italy, metropolitan area during the period from October 2008 to January 2009. Accurate ground reference rainfall estimates for two satellite pixels are obtained from a dense rain gauge network (22 rain gauges in one pixel and 16 in the other one). The evaluation is based on examination of time series, scatterplots, and survival functions, as well as measures of agreement and disagreement. The results of this study point to the importance of using the TRMM satellite for rainfall estimation. Suggestions in terms of minimum number of rain gauges required to estimate ground reference rainfall are also provided.

1. Introduction

Several studies have used the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; Huffman et al. 2007) product for applications including landslides assessment and land surface modeling (e.g., Gottschalck et al. 2005; Hong et al. 2006, 2007a,b; Collischonn et al. 2008; Crow and Bolten 2007; Curtis et al. 2007a; Su et al. 2008; Beighley et al. 2009; Kirschbaum et al. 2009; Li et al. 2009; Rahman et al. 2009a; Swenson and Wahr 2009; Tobin and Bennett 2009; Valeriano et al. 2009), hurricane rainfall (e.g., Curtis et al. 2007a; Shepherd et al. 2007; Jiang et al. 2008a,b; Jiang and Halverson 2008; Lau et al. 2008; Habib et al. 2009; Yu et al. 2009), and rainfall climatology and diurnal cycle (e.g., Curtis et al. 2007b; Dai et al. 2007; Shin et al. 2007; Ichikawa and Yasunari 2008; Kikuchi and Wang 2008; Nesbitt et al. 2008; Riddle and Cook 2008; Zhou et al. 2008; Durkee et al. 2009; Gu 2009; Endreny and Imbeah 2009; Juarez et al. 2009; Pritchard and Somerville 2009; Rahman et al. 2009b; Skok et al. 2009). The main strength of TMPA, as well as the other high-resolution merged satellite products [e.g., Precipitation Using Artificial Neural Networks (PERSIANN; e.g., Sorooshian et al. 2000), Climate Prediction Center morphing method (CMORPH; Joyce et al. 2004), National Research Laboratory Global Blended-Statistical Precipitation Analysis (NRLgeo; Turk and Miller 2005), passive microwave–infrared algorithms (PMIR; Kidd et al. 2003)], is their global coverage at fine spatial and temporal resolutions (0.25° × 0.25° and 3 hourly).

For a meaningful use of TMPA, it is important to have information about the uncertainties associated with the rainfall estimates. In the literature, different studies evaluated the accuracy of this product for different areas of the globe and at different spatial and temporal scales. As discussed in Villarini et al. (2009), in the majority of the cases these works focused on spatial and/or temporal resolutions larger than the finest available (e.g., Katsanos et al. 2004; Gottschalck et al. 2005; Dinku et al. 2007, 2008; Huffman et al. 2007; Tian and Peters-Lidard 2007; Tian et al. 2007; Xie et al. 2007; Vila et al. 2009; Zhou et al. 2008; Chokngamwong and Chiu 2008; Feidas 2010). Fewer studies examined the accuracy of TMPA at the 0.25° × 0.25° spatial scale and 3-hourly temporal scale. Villarini and Krajewski (2007) evaluated this product over one pixel in Oklahoma with respect to the average of 23 rain
gauges for a 6-yr period. Villarini et al. (2009) evaluated the TMPA product with respect to radar-based rainfall estimates over Oklahoma. Sapiano and Arkin (2009) examined performance of TMPA (as well as other high-resolution satellite rainfall products) over the U.S. Great Plains and the tropical Pacific Ocean. Habib et al. (2009) focused on six tropical storms passing over Louisiana. Koo et al. (2009) evaluated this product over South Korea, and Kubota et al. (2009) evaluated the product over Japan. Studies focusing on the evaluation of this product at its finest spatial and temporal scales are still needed.

Another element common to the vast majority of the aforementioned studies is that TMPA is evaluated at latitudes between the inclined latitude of the TRMM satellite (36° north/south). Although this product covers the tropics and midlatitudes between 50° north and 50° south, few studies have focused on geographic regions outside the TRMM orbit. The estimates from the TRMM Combined Instrument, which includes data from the precipitation radar and the Microwave Imager, are used as a source of calibration for the passive microwave data. The evaluation of this product for a region beyond the TRMM inclined orbit still requires further investigation.

Meaningful statements concerning the quality of this product are unavoidably linked to the availability of good ground reference data. The most direct and accurate way of measuring rainfall is by means of rain gauges. Rain gauge measurements are representative of only a limited area around the instrument, and a dense network is needed to capture the spatial variability of the precipitation system within a 0.25° × 0.25° pixel. Villarini and Krajewski (2007) focused on a single satellite pixel and used the average of 23 rain gauges as ground reference, with very small spatial sampling errors (uncertainties associated with the approximation of an areal value by the average of point measurements; Kitchen and Blackall 1992; Villarini et al. 2008; Villarini and Krajewski 2008). In the majority of cases, dense rain gauge networks are
not available and ground-based weather radar is used as ground reference. As shown by Villarini et al. (2009), it is important to account for the uncertainties in the radar data so as to make meaningful statements about the targeted satellite errors.

The availability of rainfall measurements by dense rain gauge networks is very limited. Few studies have attempted to provide guidance in specifying the minimum number of rain gauges that should be used when computing the ground reference rainfall. At the monthly time scale and $2.5^\circ \times 2.5^\circ$ spatial scale, Xie and Arkin (1995) suggested using five rain gauges to estimate the areal rainfall within 10% of its true value. For the same spatial and temporal resolution, Krajewski et al. (2000) suggested using 25 sensors to minimize both systematic and random errors. Following Rudolf and Schneider (2004), at the daily scale and 2.5° pixels the sampling error associated with representing the areal rainfall with the average of nine rain gauges is 30% of the areal rainfall during winter. Villarini et al. (2008) provided some information about this problem at smaller spatial and temporal scales. They considered rain gauges within a basin smaller than the TMPA pixel (about 160 km$^2$) over England, which is outside the area covered by TMPA.

In this study, I will focus on the evaluation of the research-version TMPA rainfall estimates for two pixels

![Image of correlation plots](https://example.com/correlation_plots.png)

**Fig. 2.** Plots of the spatial correlation using (top) Pearson’s $r$, (middle) Spearman’s $\rho$, and (bottom) Kendall’s $\tau$ for 3-hourly rainfall accumulations. The solid lines represent the results from fitting the data using a two-parameter exponential correlation function.
in the Rome, Italy, metropolitan area (Fig. 1) at its finest spatial and temporal scales (3 hourly and 0.25° × 0.25°). Within these two pixels there is a dense network of rain gauges, with 22 gauges in one pixel and 16 in the other. Rome is located at 41.9°N, 12.45°W, outside the area covered by TRMM.

The aim of this study is twofold: 1) to evaluate the research-version TMPA at its finest spatial and temporal scales for an area outside the TRMM coverage and 2) to provide suggestions about the number of rain gauges that should be used in evaluating the TMPA product. The paper is organized in the following way: In section 2, I describe the satellite and rain gauge data. Section 3 shows the results and is followed by section 4, in which I discuss the results of the analyses, summarize the main points, and conclude the paper.

2. Data

In this study I focus on the evaluation of two TMPA pixels over the Rome metropolitan area. The research-version TMPA products [bias corrected on a monthly basis; see Huffman et al. (2007) for details] are on a 3-h time scale for pixels of 0.25° × 0.25° (about 21 km × 27.5 km over this area). To compute the ground reference rainfall, I take advantage of a dense network of rain gauges over...
the area (Fig. 1). In pixel 1 (the western pixel) there are 22 rain gauges, and in pixel 2 (the eastern pixel) there are 16 gauges. I performed quality control of the rain gauges by comparing the rainfall values at neighboring sites, examining the storm total rainfall map, and computing the rainfall spatial correlation and checking whether any point was outside the general pattern (e.g., Fig. 2). Based on these quality-control checks, the rain gauges used in this study did not present large quality-control issues.

I compute areal estimates only if there are measurements from at least 18 rain gauges for pixel 1 and 13 for pixel 2, so that about 80% of the total number of rain gauges were working at the same time. Data are available for the period from October 2008 to January 2009 (there are 1054 pairs for pixel 1 and 1072 for pixel 2). This period includes a flooding event over Rome (Villarini et al. 2010, manuscript submitted to J. Hydrol.) that resulted in one fatality and over 150 million Euros in economic damage in the vicinity of Rome. Based on the 140-yr time series by the Collegio Romano observatory (downtown Rome), October and November of 2008 resulted in a slightly above-average monthly accumulation and December 2008 was the second wettest month in a record of 140 years (Villarini et al. 2010, manuscript submitted to J. Hydrol.). As discussed in Villarini et al. (2010, manuscript submitted to J. Hydrol.), different synoptic settings were responsible for this flood event (e.g., strong trough and southerly flow around low pressure centers).

FIG. 4. As in Fig. 3, but for pixel 2.
To evaluate how well the average of the rain gauge point measurements represents the areal rainfall, I use the variance reduction factor (VRF), which provides information about the uncertainties associated with the approximation of the areal value by the average of point measurements (e.g., Rodriguez-Iturbe and Mejia 1974; Morrissey et al. 1995; Krajewski et al. 2000). It depends on the network density, the network configuration, and the spatial correlation of the rainfall process in the area (for instance, it can take into account the less-dense rain gauge coverage in the western part of pixel 1). The first step is to compute the spatial correlation of the rainfall systems over the area during the study period. In Fig. 2, the results of the analyses of the 3-hourly rainfall spatial correlation using three different estimators, Pearson’s $r$ (top panel), Spearman’s $\rho$ (middle panel), and Kendall’s $\tau$ (bottom panel) are presented. Both Spearman’s $\rho$ and Kendall’s $\tau$ provide very similar results that differ from Pearson’s $r$. In general, the rainfall process at the 3-hourly scale decorrelates to $1/e$ at distances that are larger than the pixel size, with a decay that is slower (faster) than exponential for the Pearson’s estimator (Spearman’s and Kendall’s estimators). The main difference is that Spearman’s $\rho$ and Kendall’s $\tau$ are nonparametric estimators. The data are assumed to be Gaussian distributed when using Pearson’s $r$. The data are fitted to a two-parameter exponential function, which is used, together with information about the network density and configuration, to compute the VRF. For this period,

![Graph](image_url)

**Fig. 5.** Time series of the differences between the rain gauge averages and TMPA for the two pixels for the period from October 2008 to January 2009.
and rain gauge network, I obtain values that are smaller than 3% for both pixels independent of the selected estimator. Therefore, the areal estimate obtained by averaging the rain gauges within each pixel can be regarded as a good approximation of the true ground reference, limiting the impact of spatial sampling errors.

The TMPA rainfall product is evaluated by comparison with the rain gauge rainfall time series, scatterplots, survival functions, and measures of agreement and disagreement. The measures of agreement are three different estimates of the correlation coefficient (Pearson’s $r$, Spearman’s $\rho$, and Kendall’s $\tau$). The measures of disagreement are the root-mean-square error (RMSE), the mean absolute error (MAE), the mean error (ME), and the bias (defined as the ratio between the satellite and rain gauge sample means). Consult Conover (1999), Wilks (2006), and Hyndman and Koehler (2006) for a more extensive discussion about these metrics.

3. Results

In this section, I show the results of the rain gauge–satellite comparison and provide some guidance on the number of rain gauges that should be used when evaluating the satellite estimates.

Figures 3 and 4 are the time series for the TMPA rainfall product and the rain gauge averages for pixels 1 and 2. The satellite product is most similar to the rainfall pattern of the rain gauge time series during October and November (top two panels), and is able to capture most of the rainfall variability. The TMPA tends to underestimate the rainfall values toward the end of October and overestimate the peaks at the beginning of November. This could be ascribed to the changes in bias correction from one month to the other. On the other hand, during December and January, there are much larger discrepancies between rain gauges and satellite estimates. In particular, TMPA misses the December event that caused flooding over Rome. This is in agreement with Sapiano and Arkin (2009), who found fewer rain events in TMPA relative to other high-resolution satellite products. These discrepancies are highlighted in the time series of the differences between the rain gauge and satellite rainfall estimates (Fig. 5). TMPA tends to underestimate rainfall during most of this period, with the notable exception of November. However, there is close agreement in the discrepancies for the two pixels, suggesting that these differences are more likely due to the estimation of rainfall and bias correction than to the rainfall process variability over this area.

Figure 6 (top panel) is a scatterplot between the rain gauge–based areal averages and satellite estimates for both pixels. There is large scatter, with several data points spread along the $x$ axis (most of them correspond to the rainfall values for the month of December), which is due to both the satellite uncertainties and the noise associated with the limited sample size used in this study. Few data points are spread around the 45° line. Table 1 is a summary of basic statistics (mean, standard deviation, and percentage of zeros) for both rain gauges and TMPA [the 90% confidence intervals on these estimates are computed by means of bootstrap with replacement (e.g., Efron and Tibshirani 1997)]. Independent of the pixel,
the rain gauge–based mean rainfall rate is larger, with values of 0.67 mm (3 h)$^{-1}$, when compared with the satellite [about 0.26 mm (3 h)$^{-1}$]. The standard deviation is larger as well, with values of 2.99 and 2.97 mm (3 h)$^{-1}$ for the rain gauges and 2.57 and 2.37 mm (3 h)$^{-1}$ for the satellite. The satellite has a much larger percentage of zero rainfall periods (98%) when compared with the rain gauges, which show percentages of zero rainfall periods of less than 60%.

In Oklahoma, Villarini and Krajewski (2007) showed that the rain gauge survival function matched well with the TMPA survival function. For six tropical storms over Louisiana, Habib et al. (2009) found that the frequencies of high rainfall were smaller when compared with the ground reference. Figure 6 (bottom panel) is the survival functions for the two pixels. There is good agreement between the two pixels, for both the ground reference and TMPA examined separately. There are large differences between the rain gauges and the satellite product in each pixel. However, these discrepancies are more apparent at lower rainfall, with TMPA not detecting the small rainfall values. The survival function, together with the percentage of zeros in Table 1, points to problems associated with the detection of small rainfall values.

Table 2 is a summary of the statistics used to evaluate the TMPA product. The values in parentheses represent the 5th and 95th percentiles computed by means of bootstrapping.

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Table 2 is a summary of the results from the comparison between rain gauges and TMPA. The correlation coefficients tend to be smaller than have been observed in other areas of the globe (e.g., Villarini and Krajewski 2007; Villarini et al. 2009; Habib et al. 2009; Sapiano and Arkin 2009), with values of Pearson’s $r$ of less than 0.40 and values of Spearman’s $\rho$ and Kendall’s $\tau$ between 0.20 and 0.25. These results are expected given the visual inspection of the scatterplot in Fig. 6 (top panel). Apart from the importance of using the TRMM satellite, it is also possible that these estimates suffer from rainfall estimation during the cold season (e.g., Villarini and Krajewski 2007; Villarini et al. 2009; Sapiano and Arkin 2009). There is a bias (defined as the ratio between TMPA and rain gauge sample means) of about 0.4, indicating a significant underestimation by TMPA. The bias values are smaller than those found by Villarini and Krajewski (2007) and Villarini et al. (2009) over Oklahoma. The RMSE is about 5 times the rain gauge mean, and the MAE is slightly larger than 1. These results are comparable to values found by Villarini and Krajewski (2007) and Villarini et al. (2009) in Oklahoma.

To provide some guidance concerning the number of rain gauges necessary to compute a reasonably accurate areal rainfall estimate, the areal rainfall estimate is computed using an increasing number of rain gauges. The simplest case is one rain gauge (there are 22 possible values for pixel 1 and 16 for pixel 2) as representative of ground reference rainfall. For two rain gauges, the ground reference is computed as the average of two rain gauge measurements [given $n$ rain gauges, there is a total of $n(n - 1)/2$ possible combinations]. When using more than two rain gauges, I include 500 possible combinations for pixel 1 and 120 for pixel 2. I use the values of Pearson’s correlation coefficient, MAE, and RMSE computed using all the rain gauges as reference values. The results are summarized in Fig. 7 in the form of box plots. The limits of the box represent the 25th and 75th percentiles; the line and square within the box are the median (50th percentile) and mean, respectively. The limits of the whiskers identify the 5th and 95th percentiles.

Based on these results, there is a consistent picture across the three metrics and for both pixels. As expected, there is large variability when using a small number of rain gauges (the differences between pixel 1 and pixel 2 could be due to the different rain gauge density and configuration). There is also a significant bias, with the mean and median values different from the target value. As the number of rain gauges used to compute the areal average is increased, the spread decreases as well as the bias. Based on these results, I would suggest using at least

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**Table 1.** Summary with mean, standard deviation, and percentage of zeros for the satellite and rain gauge datasets for the two pixels. The values in parentheses represent the 5th and 95th percentiles computed by means of bootstrapping.

<table>
<thead>
<tr>
<th></th>
<th>Pixel-1 rain gauge</th>
<th>Pixel-1 TMPA</th>
<th>Pixel-2 rain gauge</th>
<th>Pixel-2 TMPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean $[\text{mm (3 h)}^{-1}]$</td>
<td>0.67 (0.54; 0.88)</td>
<td>0.26 (0.14; 0.42)</td>
<td>0.67 (0.53; 0.84)</td>
<td>0.27 (0.16; 0.41)</td>
</tr>
<tr>
<td>Std dev $[\text{mm (3 h)}^{-1}]$</td>
<td>2.99 (2.14; 3.95)</td>
<td>2.57 (1.30; 3.84)</td>
<td>2.97 (1.94; 3.98)</td>
<td>2.37 (1.37; 3.27)</td>
</tr>
<tr>
<td>Percentage of zeros</td>
<td>56%</td>
<td>98%</td>
<td>58%</td>
<td>98%</td>
</tr>
</tbody>
</table>

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**Table 2.** Summary of the statistics used to evaluate the TMPA product. The values in parentheses represent the 5th and 95th percentiles computed by means of bootstrapping.

<table>
<thead>
<tr>
<th></th>
<th>Pixel 1</th>
<th>Pixel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson’s $r$</td>
<td>0.37 (0.17; 0.61)</td>
<td>0.39 (0.21; 0.56)</td>
</tr>
<tr>
<td>Spearman’s $\rho$</td>
<td>0.23 (0.18; 0.28)</td>
<td>0.25 (0.20; 0.29)</td>
</tr>
<tr>
<td>Kendall’s $\tau$</td>
<td>0.20 (0.16; 0.25)</td>
<td>0.22 (0.18; 0.26)</td>
</tr>
<tr>
<td>RMSE $[\text{mm (3 h)}^{-1}]$</td>
<td>3.22 (2.35; 4.04)</td>
<td>3.02 (2.32; 3.72)</td>
</tr>
<tr>
<td>MAE $[\text{mm (3 h)}^{-1}]$</td>
<td>0.75 (0.59; 0.93)</td>
<td>0.71 (0.56; 0.87)</td>
</tr>
<tr>
<td>ME $[\text{mm (3 h)}^{-1}]$</td>
<td>0.43 (0.25; 0.60)</td>
<td>0.40 (0.25; 0.57)</td>
</tr>
<tr>
<td>Bias</td>
<td>0.39 (0.21; 0.60)</td>
<td>0.40 (0.25; 0.59)</td>
</tr>
</tbody>
</table>
five rain gauges to obtain a reasonably accurate approximation of the area-averaged rainfall. Nonetheless, it is worth clarifying that this suggestion should be considered as a lower bound, given the large spatial correlation exhibited by the rainfall process in the area during this time period (Fig. 2).

4. Summary and conclusions

In this study I evaluated the rainfall estimates obtained from the TMPA satellite product at its finest spatial and temporal resolutions ($0.25^\circ \times 0.25^\circ$ and 3 hourly). I focused on two pixels over the Rome metropolitan area.

Fig. 7. Box plots showing the dependence of the accuracy of the satellite evaluation on the number of rain gauges for (left) pixel 1 and (right) pixel 2. In each panel, the solid dark gray line represents the value obtained by using all of the rain gauges within each pixel (see Table 2).
with 22 and 16 rain gauges, respectively, over the period from October 2008 to January 2009. In summary, the major findings of this paper are as follows:

- There are large uncertainties associated with the TMPA product over this area. Comparison of the satellite and rain gauge time series shows that TMPA is able to capture some of the pulses of rainfall, even though, depending on the monthly bias correction, it tends either to underestimate or to overestimate the rainfall values with respect to the rain gauges.
- The largest discrepancies between the rain gauge and TMPA survival functions are for small rainfall values.
- The agreement and disagreement metrics used in this study suggest a poorer performance of the TMPA when compared with other areas of the globe. Because this area is outside the orbit of TRMM, these results underline the importance of TRMM satellite sensors for accurate satellite rainfall estimates.
- For the finest spatial and temporal resolution, I suggest using at least five rain gauges when computing the areal-average rainfall used as ground reference. This suggestion should be considered as a lower bound given the large spatial correlation of the rainfall systems over this area.
- One shortcoming of this study is represented by the short time period considered (4 months). Future studies should aim at extending these analyses over a longer time horizon and additional high-resolution satellite rainfall products.

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