



# Comparison of the performance of estimated precipitation data via remote sensing in the Midwest Region of Brazil

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## Abstract

Consistent precipitation data are essential for hydrological studies and planning of diverse socioeconomic activities. However, the low density of in situ gauges, areas of difficult access and high percentage sampling failures hinder an effective hydrological monitoring in most Brazilian municipalities. The objective of the present study is to compare the performance of precipitation estimates from the Global Precipitation Measurement (GPM), Tropical Rainfall Measurement Mission (TRMM) and Global Precipitation Climatology Project (GPCP) satellites in relation to precipitation data observed on the surface on daily, monthly and seasonal time scales, from 2011 to 2019 in the capital of Mato Grosso do Sul (MS), Midwest Region of Brazil. Seven statistical indicators were used. In general, the performance of the GPM and GPCP estimates are similar and better than the TRMM estimates on the daily scale. On the monthly and seasonal scales, the GPM estimates stand out from the others. It was possible to verify that all precipitation estimates are more reliable in larger time scales and drier periods. Finally, it is concluded that the precipitation estimates of the GPM, TRMM and GPCP satellites can be an alternative in areas that do not have in situ gauges or need to fill sampling failures. Nevertheless, it is recommended to expand the in situ gauges network in Brazil, mainly in the Midwest Region, in order to allow new spatially and temporally more representative studies.

**Keywords** GPM · TRMM · GPCP · Estimate · Precipitation

## 1 Introduction

The availability of consistent precipitation data with high spatial and temporal resolution is essential for planning various socioeconomic activities, such as agriculture, livestock, energy generation and identification of areas at risk for hydrological disasters (Prakash et al. 2018; Rozante et al. 2018). However, traditional precipitation measurements by in situ gauges are relatively sparse and poorly distributed over the Earth's surface, especially in areas of difficult access and in developing countries (Rozante et al. 2018; Rodrigues et al. 2020a). In addition, their databases generally have a high percentage of sampling failures, limiting the accuracy of hydrological studies (Rodrigues et al. 2021).

In this scenario, satellite precipitation estimate products emerge as promising alternatives for more accurate

hydrological monitoring, because they allow continuous measurements of precipitation with virtually global coverage and high spatio-temporal resolution, regardless of the less accessible regions (Tan and Santo 2018; Wang et al. 2017a; Rodrigues et al. 2020a, 2020b), such as the Integrated Multisatellite Retrievals Final Run (IMERG-F) from the Global Precipitation Measurement (GPM) mission, the Multi-satellite Precipitation Analysis (TMPA) from the Tropical Rainfall Measurement Mission (TRMM) and the Global Precipitation Climatology Project Daily (GPCPDAY) and Global Precipitation Climatology Project Satellite-Gauge Combined Precipitation (GPCPMON) from the Global Precipitation Climatology Project (GPCP). These products have been widely used in regional and global meteorological and climatological studies (Singh et al. 2018, 2020; Rodrigues et al. 2020b; Wang et al. 2021; Yu et al. 2021).

Nevertheless, according to Franchito et al. (2009), Thiemi et al. (2013) and Melo et al. (2015), random errors and uncertainties can occur in satellite precipitation estimates. Salles et al. (2019), Rodrigues et al. (2020a) and Araujo Palharini et al. (2021) evaluated the precipitation estimates from the TRMM and GPM satellites in different regions of Brazil and

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concluded, in general, that the accuracy of these estimates may be related to factors such as topography, type of precipitation and local climate of the study area. Thus, a performance evaluation is necessary to identify the potential and possible limitations of using satellites to estimate precipitation at the site of interest before application (Franchito et al. 2009; Tan and Santo 2018; Silva et al. 2019).

Additionally, Tan and Santo (2018) affirm that a preliminary validation of precipitation estimates by remote sensing is essential to promote improvements in algorithms and in the development of satellite sensors. Since then, several validation studies of satellite precipitation estimates have been carried out in various parts of the world, such as Asia (Hosseini-Moghari and Tang 2020), Europe (Lockhoof et al. 2014), North America (Tian et al. 2010) and South America (Reis et al. 2017; Moraes and Gonçalves 2021; Pedreira Junior et al. 2021). In recent years, many of these validation studies have focused on TMPA (Melo et al. 2015; Reis et al. 2017; Abreu et al. 2020; Moraes and Gonçalves 2021), IMERG (Gaona et al. 2016; Sahlu et al. 2016; Gadelha et al. 2019; Rodrigues et al. 2021) and GPCP (Saldanha et al. 2015; Silva et al. 2019) products in large regions or watersheds.

Nonetheless, the performance of the GPM IMERG product, more recent in relation to the others, was little analysed in Brazilian watersheds (Rodrigues et al. 2021). New studies with longer periods of recording GPM data are needed for better qualitative analysis (Reis et al. 2017). At the same time, it is necessary to increase attention to hydrological studies on small areas with scarce data on in situ precipitation (Reis et al. 2017), due to the occurrence of floods after heavy rains, especially in urban areas. However, studies evaluating the accuracy of precipitation data obtained by remote sensing versus data measured in situ are scarce in Brazil, especially in the Midwest Region and in the state of Mato Grosso do Sul (MS) (Oliveira Júnior et al. 2021).

In fact, no studies were identified regarding the comparison of different databases of precipitation estimates by satellites exclusively in the state of MS, whose capital has approximately one million people (Brazilian Institute of Geography and Statistics—IBGE 2021) and has been suffering from extreme hydrological disasters, such as floods in your urban area. Therefore, the objective of this study was to compare the performance of precipitation estimates by GPM, TRMM and GPCP satellites in relation to data observed by in situ gauges, on daily, monthly and seasonal time scales in the capital of MS.

## 2 Methodology

### 2.1 Study area

The study area is inserted in the municipality of Campo Grande, located in the central part of the state of MS,

Midwest Region of Brazil, according to Fig. 1. The municipality occupies an area of 8,082.978 km<sup>2</sup> with estimated population of 916,001 people (IBGE 2021) and has an average annual precipitation of 1570 mm and altitude between 500 and 675 m (Municipal Agency for the Environment and Urban Planning—PLANURB 2021). The climate of Campo Grande, according to the Köppen classification, is in the transition range between the humid mesothermal subtype (Cfa) without drought or small drought and the humid tropical subtype (Aw), with a rainy season in the summer and a dry season in the winter (PLANURB 2021).

### 2.2 Satellite precipitation products

Satellite precipitation estimate data were obtained from the Giovanni portal of the National Aeronautics and Space Administration (NASA) (<https://giovanni.gsfc.nasa.gov/giovanni/>). Products from the TRMM, GPM and GPCP were used. TRMM satellite orbits at an angle of 35° in relation to the Equator and provides precipitation products between latitudes 50° North and 50° South, with 3 h, daily or monthly temporal resolution and 0.25° × 0.25° or 0.50° × 0.50° spatial resolution of according to the chosen product (Huffman et al. 2007). In this study, Multi-satellite Precipitation Analysis (TMPA) product of the seventh version (3B42V7) TRMM was used, with 0.25° × 0.25° spatial resolution and daily/monthly temporal resolution.

The GPM mission stands out for the use of a constellation of international satellites, which aim at a more accurate monitoring of rain and snow (Huffman et al. 2015). Unlike TRMM, the GPM satellite orbits at an angle of 65° and provides products with precipitation and snow information across the globe (Hou et al. 2014), with 30 min, daily or monthly temporal resolution, and 0.10° × 0.10° spatial resolution. In this study, Integrated Multisatellite Retrievals Final Run (IMERG-F) version 6 product of GPM level 3 was used, with 0.10° × 0.10° spatial resolution and daily/monthly temporal resolution.

GPCP seeks to maintain a homogeneous global record of precipitation. It is formed based on rainfall information from more than 6700 surface weather stations distributed around the world and precipitation estimates from the geostationary satellites (Silva et al. 2019). Currently, GPCP provides products with daily and monthly temporal resolution and 0.50° × 0.50° spatial resolution. In this study, GPCP version 3.2 Daily Precipitation Data Set (GPCP-DAY) and GPCP version 3.2 Satellite-Gauge Combined Precipitation Data Set (GPCP-MON) products were used, with daily and monthly temporal resolution, respectively.

It is important to note that there are other alternative methods to estimate precipitation, such as the Global Land

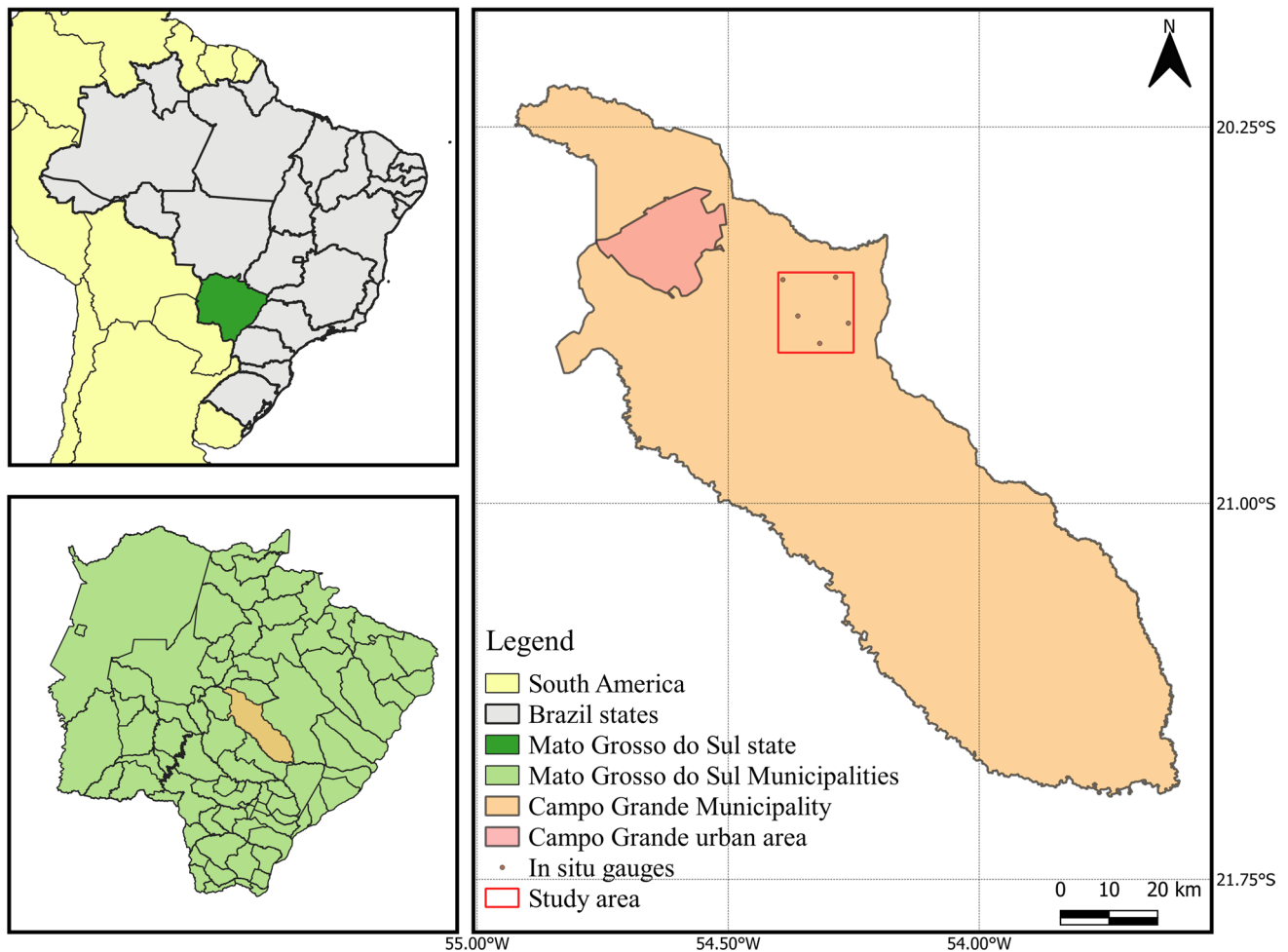


Fig. 1 Study area

Data Assimilation (GLDAS) and the Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis products. However, they tend to present a high level of uncertainty when convective precipitation regimes occur (Ferguson et al. 2012; Bosilovich et al. 2017). On the other hand, according to Khodadoust Siuki et al. (2017) and Almagro et al. (2021), remote sensing products (TRMM, GPM and GPCP) provide more reliable precipitation estimates and, therefore, were prioritized in the present study. In fact, in a study carried out in the state of Mato Grosso, Brazil, Pedreira Junior et al. (2021) concluded that the TRMM, GPM and GPCP estimates obtained more satisfactory results than the GLDAS and MERRA products, since remote sensing products assimilate a higher frequency of high intensity precipitation events (Sun et al. 2018), being common the occurrence of convective rains in the region studied, similar to Campo Grande-MS. Almagro et al. (2021) concluded that satellite-based precipitation products are more reliable than ERA-5 for five of six biomes of Brazil.

Concomitantly, Andrade et al. (2022) also concluded that satellite-based precipitation products (TMPA, IMERG and CHIRPS) generally outperform model-based precipitation products (TerraClimate with a spatial resolution of  $0.04^\circ$  and ERA-5 Land with a spatial resolution of  $0.1^\circ$ ). The authors say that a possible explanation is that the CHIRPS and IMERG products, for example, undergo surface calibration (Xu et al. 2022). Additionally, CHIRPS uses TMPA 3B42 V7 data to calibrate global precipitation estimates (Huffman et al. 2007; Katsanos et al. 2016). However, regarding the CHIRPS product, Cavalcante et al. (2020) concluded in a study covering nine Brazilian states that, despite having a spatial resolution of  $0.05^\circ$ , this product does not represent the trends in rainfall indices well and is not recommended for projects of hydraulic structures and studies of flooding and extreme events of precipitation. At the same time, Paredes-Trejo et al. (2017) concluded that the CHIRPS product has a poor ability to detect rainfall in the Northeast Region of Brazil, as well as López-Bermeo et al. (2022)

in Colombia, who reached results that infer that CHIRPS is an acceptable source of precipitation information for an annual scale, but unsatisfactory for a daily scale. Therefore, the CHIRPS product was not used in this study.

### 2.3 In situ gauges

To evaluate the precipitation estimates of the products of the TRMM, GPM and GPCP satellites, a set of precipitation data observed at 5 surface weather stations (in situ gauges) was used as reference. These stations are located approximately 20 km from the urban area of the municipality of Campo Grande and are managed by the Laboratory of Hydrology, Erosion and Sediments (HEROS) of the Faculty of Engineering, Architecture and Urbanism and Geography (FAENG) of the Federal University of Mato Grosso do South (UFMS). Table S1, available in supplementary section, presents information about the localization in situ gauges and percentage of sampling failure in the rainfall time series.

### 2.4 Statistical analysis

The performance of the TRMM, GPM and GPCP precipitation estimates in relation to the data observed in the in situ gauges was evaluated from August 2011 to December 2019 through the following statistical indicators: mean absolute error (MAE), root mean square error (RMSE), Pearson's correlation coefficient ( $r$ ), Willmott index ( $d$ ), probability of detection (POD), false alarm rate (FAR) and critical success index (CSI). Indicators used for comparison and validation of various precipitation databases around the world (Reis et al. 2017; Rozante et al. 2018; Tan and Santo 2018; Gadelha et al. 2019; Paredes-Trejo et al. 2019; Amorim et al. 2020; Pedreira Junior et al. 2021; Rodrigues et al. 2021).

The MAE and the RMSE quantify the errors of the estimated data in relation to the observed ones, according to Eqs. 1 and 2, respectively. The MAE records, in units of the analysed variable, the level of general agreement between the two sets of data, regardless of the sign. The RMSE measures the square of the deviation between the data, being more sensitive to larger errors, better describing the accuracy of the satellites. The lower the result of these indicators, the better the satellite's performance to represent the precipitation dataset (Tan and Santo 2018; Rodrigues et al. 2021).

The  $r$  measures the degree of linear correlation between estimated and observed precipitation, Eq. 3. The  $r$  values were classified as proposed by Hinkle et al. (2003) and used by Torres et al. (2020) for validation of different precipitation databases in Brazil. The Table S2 presents the  $r$  classification used in this work. The  $d$  shows the agreement between the estimated and observed data, ranging from 0 to 1, that is, the worst and best performance of the estimates, respectively (Willmott 1981). The  $d$  is calculated from Eq. 4.

$$MAE = \frac{\sum_{i=1}^n |E_i - O_i|}{n} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (E_i - O_i)^2}{n}} \quad (2)$$

$$r = \frac{\sum_{i=1}^n (E_i - \bar{E}) \cdot (O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (E_i - \bar{E})^2} \sqrt{\sum_{i=1}^n (O_i - \bar{O})^2}} \quad (3)$$

$$d = 1 - \frac{\sum_{i=1}^n (E_i - O_i)^2}{\sum_{i=1}^n (|E_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (4)$$

where  $E_i$  = estimated precipitation by satellite;  $O_i$  = observed precipitation by in situ gauge;  $n$  = number of observations;  $\bar{E}$  = average estimated precipitation and  $\bar{O}$  = average observed precipitation.

POD, FAR and CSI were calculated to assess the satellite precipitation detection capability (Ebert et al. 2007; Wilks 2011), based on Eqs. 5, 6 and 7, respectively. According to Tan and Santo (2018), POD is known as the hit rate, calculated by the ratio between the number of precipitation occurrences correctly detected by the satellite and the total number of actual precipitation events. The FAR defines the fraction of events that were predicted but did not occur, being calculated by the ratio between the number of falsely detected precipitation events (false alarm) and the total number of detected precipitation events, while CSI measures the overall fraction of precipitation events correctly detected by the satellite.

The POD, FAR and CSI values range from 0 to 1, with 1 being the perfect score for POD and CSI and 0 being perfect for FAR (Tan and Santo 2018). Days with precipitation and without precipitation were differentiated by applying a common limit of 1 mm/day (Yong et al. 2010), as adopted in validation studies of precipitation estimates by satellites (Paredes-Trejo et al. 2019; Rodrigues et al. 2021).

$$POD = \frac{a}{a + c} \quad (5)$$

$$FAR = \frac{b}{a + b} \quad (6)$$

$$CSI = \frac{a}{a + b + c} \quad (7)$$

where  $a$  = days with observed and estimated rain,  $b$  = days with estimated rain, but without observed rain,  $c$  = days with observed rain, but without estimated rain and  $d$  = days without observed and estimated rain.

It is important to highlight that in situ gauges measure precipitation punctually, and there may be considerable differences from one gauge to another. On the other hand, satellites estimate the average precipitation in a pixel (10 km × 10 km – GPM, 25 km × 25 km – TRMM and 50 km × 50 km – GPCP). According to Duan et al. (2016), there is a clear problem of scale incompatibility between point-based precipitation data (in situ gauges) and grid products (satellites), and it is common in evaluation and validation studies of precipitation data, to increase the area of influence of the point-based rainfall data for the same grid scale that rainfall products from satellites. In this scenario, there are many interpolation techniques to achieve this scaling up, such as simple algorithmic averaging (Xie and Xiong 2011), Thiessen polygon (Liu et al. 2015), inverse distance weighting (IDW) (Hu et al. 2014) and the Kriging method (Khandu et al. 2016). However, each interpolation method has its advantages and disadvantages, and its performance depends on several factors (Hofstra et al. 2008) and varies from region to region (Duan et al. 2016).

Hence, the specialized literature has used numerous methodologies to compare precipitation data estimated by remote sensing and data observed at the surface, since there is no standardized methodology for verifying and analysing these data (Feitosa and Oliveira 2020). Duan et al. (2016) and Chen et al. (2018) say that it is practically impossible to identify an optimal method applicable in all areas of study. In this work, Thiessen polygon method was used because it is relatively easy to implement and its application is popular in studies of evaluation and validation of precipitation data in Brazil, as Curtarelli et al. (2014), Reis et al. (2017), Moraes and Gonçalves (2021) and Brasil Neto et al. (2022).

In this work, we chose to compare the daily, monthly and seasonal averages of the observed and estimated data from August 24, 2011, to December 31, 2019. To obtain the average precipitation of the in situ gauges, the Thiessen polygon method was applied in the Quantum Geographic Information System (QGIS) software version 3.22.5 (QGIS 2022), as well as Moraes and Gonçalves (2021), in which the average precipitation is calculated by weighting the rainfall values of each gauge for its area of influence (WMO 1994). Finally, it is important to emphasize that the density of in situ gauges distributed in the Midwest Region is low (Gadelha et al. 2019); consequently, we had difficulty finding gauges with time series filled in without sampling failures. Concomitantly, Tang et al. (2018) and Gadelha et al. (2019) highlight that errors increase when comparing precipitation data estimated via satellite and observed on the surface in areas with low density of gauges.

Therefore, in this work, it was decided to use the same geographic coordinates (–54.4W, –20.7S, –54.25W, –20.54S, Fig. 1) both to delimit the Thiessen polygons from the gauges and to download the precipitation estimates via

satellite on the website (<https://giovanni.gsfc.nasa.gov/giovanni/>), in order to standardize the area analysed, increase the density of in situ gauges in the evaluated area and not compromise the results. Another interesting point to highlight is that Thiessen polygons were generated daily according to the gauges with filled precipitation data, changing the number of in situ gauges over the study period (Gadelha et al. 2019). That is, if on day X the five gauges had data, then the Thiessen polygons were generated considering the five points. If on day Y, a gauge had sampling failure, it was disregarded that day and the Thiessen polygons were generated based on 4 gauges. This detailed analysis was performed every day of the studied period.

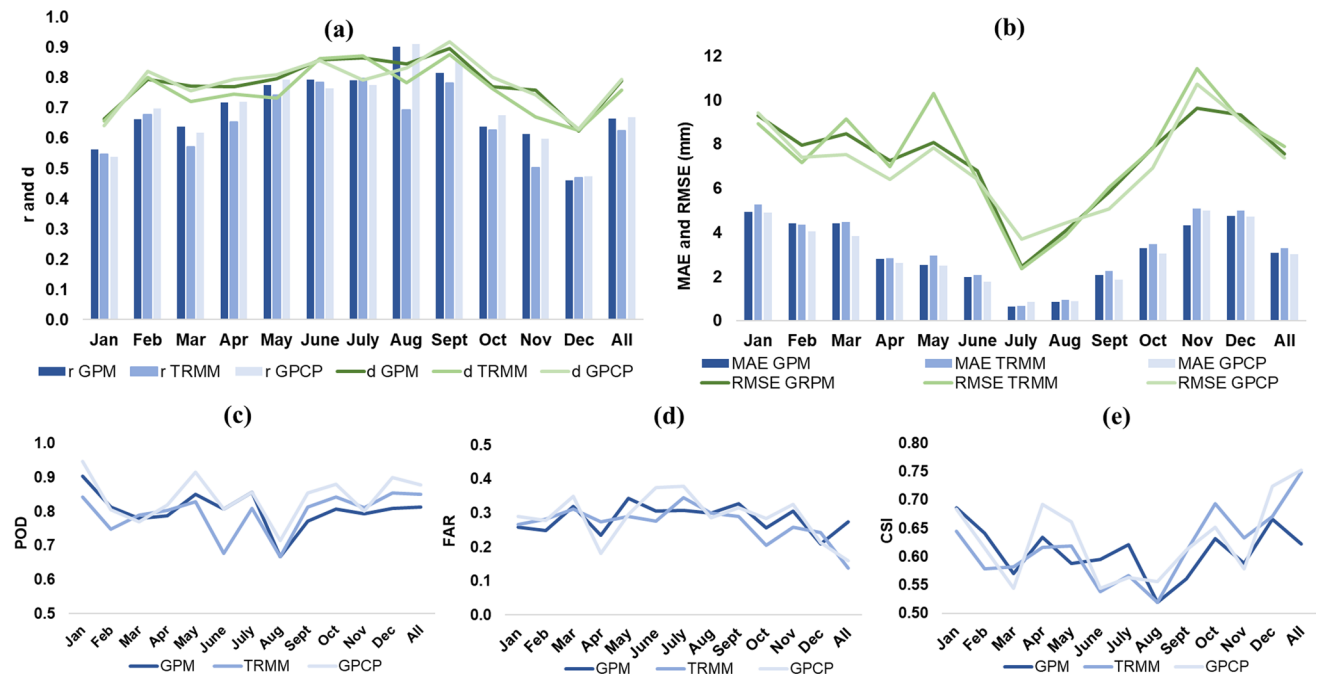
## 3 Results and discussion

### 3.1 Daily analysis

Figure 2 shows the results of  $r$ ,  $d$ , MAE, RMSE, POD, FAR and CSI of the precipitation estimates from the GPM, TRMM and GPCP satellites when compared to the precipitation data observed on the surface on a daily scale, according to the month and in general (every day of the study period regardless of the month). Overall, the daily precipitation estimates showed moderate correlation with the precipitation data observed on the surface, since the  $r$  of the GPM, TRMM and GPCP satellites were 0.67, 0.62 and 0.67, respectively. These results corroborate with Sahlu et al. (2016), Sharifi et al. (2016), Kim et al. (2017), Wang et al. (2017b), Tan and Santo (2018), Hosseini-Moghari and Tang (2020) and Le et al. (2020) who found a moderate correlation between GPM estimated data and those observed on the surface. However, the TRMM daily  $r$  found in this work is slightly lower than that found by Reis et al. (2017) in the Southeast Region of Brazil ( $r=0.70$ ).

The daily data estimated from April to September obtained the best results of correlation and agreement with the data observed on the surface, mainly from the GPM ( $0.72 < r < 0.90$  and  $0.77 < d < 0.90$ ) and GPCP ( $0.72 < r < 0.91$  and  $0.79 < d < 0.92$ ). The months from November to January were responsible for the worst daily results of  $r$  and  $d$  for the GPM ( $0.46 < r < 0.61$  and  $0.62 < d < 0.76$ ), GPCP ( $0.47 < r < 0.60$  and  $0.63 < d < 0.74$ ) and TRMM ( $0.47 < r < 0.55$  and  $0.63 < d < 0.67$ ) satellites, as verified by Abreu et al. (2020) in their work on validating TRMM data in MS.

It is worth mentioning that many convective rains occur in the period from October to December in the state of MS (Pessi et al. 2019), and this can compromise the results, because the surface weather stations measure rainfall in a punctual way, while satellites average over a given area



**Fig. 2** Results of  $r$  and  $d$  (a), MAE and RMSE (b), POD (c), FAR (d) and CSI (e) of GPM, TRMM and GPCP precipitation estimates in relation precipitation data observed in surface on daily scale

according to their spatial resolution. In addition, Tan and Santo (2018) highlight that monthly rainfall gauges are used to calibrate the GPM IMERG product, and such calibration obviously does not represent daily rainfall well, especially in regions characterized by high spatial and temporal variability of precipitation.

With regard to the MAE and RMSE, the GPCP daily precipitation estimates performed better in most months and in the overall analysis compared to the GPM and TRMM estimates. The months from April to September had the lowest MAEs for the three satellites ( $MAE < 3.00$  mm), mainly in June, July and August, while from November to March had the highest daily MAEs. The lowest RMSEs occurred in the daily estimates from June to September and the highest from November to March and May. In general, the months with the highest daily errors showed seasonality compatible with the period of intense rainfall (summer in the southern hemisphere), while the dry period (winter in the southern hemisphere) presented smaller errors (Reis et al. 2017).

In the general context, without division by month, the MAEs of the GPM, TRMM and GPCP satellites were 3.08 mm, 3.28 mm and 3.00 mm, respectively, while the RMSEs were 7.55 mm, 7.90 mm and 7.36 mm, respectively. More satisfactory results than the 12.65 mm (GPM) and 12.54 mm (TRMM) RMSEs found by Amorim et al. (2020) in a watershed located in the state of Goiás, Midwest Brazil, and RMSEs of 12.00 mm (GPM) and 15.40 mm (TRMM) identified by Le et al. (2020) in

Vietnam. On the other hand, they are superior to the 6.60 mm RMSE (TRMM) found by Reis et al. (2017) in the Southeast Region of Brazil and to the 3.85 mm RMSE (GPM) identified by Hosseini-Moghari and Tang (2020) in Iran.

GPCP showed better performance in detecting daily rainfall greater than 1 mm ( $POD = 0.88$ ), in relation to GPM and TRMM ( $POD$  of 0.81 and 0.85, respectively). In addition, GPCP obtained a FAR of 0.16 and a CSI of 0.75, that is, low false alarm rate and high precipitation hits rate, standing out in relation to the other two satellites in the general scenario, whereas Pedreira Junior et al. (2021) concluded better rain detection performance for the TRMM satellite compared to the GPM and GPCP in the state of Mato Grosso. In a study conducted throughout Brazil, Gadelha et al. (2019) found good agreement from the GPM satellite in detecting daily precipitation events in most of the country, with  $POD$  and  $CSI$  values greater than 0.6. Digging deeper into a daily analysis according to each month, the highest  $POD$  was 0.95 (January, GPCP) and the lowest 0.67 (August, GPM and TRMM), highest FAR 0.38 (June and July, GPCP) and lowest 0.18 (April, GPCP) and higher  $CSI$  0.72 (December, GPCP) and lower 0.52 (August, GPM and TRMM).

From the analysis of all statistical indicators on the daily scale, it is possible to infer that the precipitation estimates from the GPM and GPCP satellites are similar and more reliable than the TRMM estimates in the study area of the

present work. Incidentally, Rozante et al. (2018) and Le et al. (2020), in studies carried out in Brazil and Vietnam, respectively, concluded that the GPM IMERG product performs better for daily precipitation estimates compared to the TRMM TMPA product. Despite this, it is worth mentioning that the algorithms of the GPM, TRMM and GPCP satellites need additional improvements to carry out daily precipitation estimates (Reis et al. 2017; Tan and Santo 2018) in the Midwest Region of Brazil (Gadelha et al. 2019), because excellent results were not found for the indicators calculated on this time scale, as highlighted by Silva et al. (2019) and Pedreira Junior et al. (2021). According to Gadelha et al. (2019) this may be associated with the low density of in situ gauges distributed in the Midwest Region and used as a reference on the surface.

### 3.2 Monthly analysis

Figure 3 shows the results of  $r$ ,  $d$ , MAE and RMSE of the precipitation estimates from the GPM, TRMM and GPCP satellites when compared to the precipitation data observed on the surface on a monthly scale. In general, monthly precipitation estimates have a strong correlation with surface observed data, since the  $r$  from the GPM, TRMM and GPCP satellites were 0.78, 0.74 and 0.71, respectively. These results corroborate with Reis et al. (2017), Torres et al. (2020) and Pedreira Junior et al. (2021) who found high correlations of the TRMM, GPCP and GPM monthly data, respectively, in relation to the precipitation data observed on the surface. Furthermore, Silva et al. (2019) and Pedreira Junior et al. (2021) concluded that the TRMM and GPM data present better correlations with the in situ observed data than the GPCP estimated data on the monthly scale.

The monthly precipitation estimates from April to September obtained the best results of correlation and agreement with the surface observed data in the three satellites

analysed, with a slight advantage to the GPM ( $0.75 < r < 0.99$  and  $0.79 < d < 0.98$ ) when compared to others. By contrast the months from October to March were responsible for the worst monthly  $r$  and  $d$  results for GPM ( $0.34 < r < 0.65$  and  $0.49 < d < 0.75$ ), GPCP ( $0.13 < r < 0.53$  and  $0.23 < d < 0.68$ ) and TRMM ( $0.06 < r < 0.66$  and  $0.11 < d < 0.67$ ).

Regarding the MAE and RMSE, the GPM monthly precipitation estimates performed better in most months and in the overall analysis. The months from July to September presented the lowest MAEs for the three satellites (MAE < 30.00 mm), while from November to March the highest MAEs occurred. The lowest RMSE occurred in the monthly estimates of February and from June to September, whereas the highest occurred from November to January and March.

In the general context, the monthly MAEs of the GPM, TRMM and GPCP satellites were 36.01 mm, 42.22 mm and 43.43 mm, respectively, while the monthly RMSEs were 50.79 mm for GPM, 59.88 mm for TRMM and 61.49 mm for GPCP. That is, higher monthly error linked to GPCP estimates and lower to GPM estimates, as verified by Pedreira Junior et al. (2021) in the state of Mato Grosso, Brazil (GPCP RMSE close to 60 mm, TRMM RMSE = 48.75 mm and GPM RMSE = 45.26 mm on the monthly scale). The RMSEs found in this work are close to the monthly RMSEs found by Amorim et al. (2020) for the GPM IMERG product (58.09 mm) and, especially, TRMM TMPA (59.61 mm), in a watershed located in the Midwest Brazilian. On the other hand, the TRMM monthly MAE in this work is lower than that identified in the Southeast Region of Brazil (MAE = 79.13 mm) by Reis et al. (2017).

From the analysis of all statistical indicators on the monthly scale, it is possible to conclude that the GPM precipitation estimates are more reliable than the TRMM and GPCP estimates in the study area of the present work, corroborating with results found by Pedreira Junior et al. (2021) in the state of Mato Grosso, Brazil, Amorim et al. (2020)

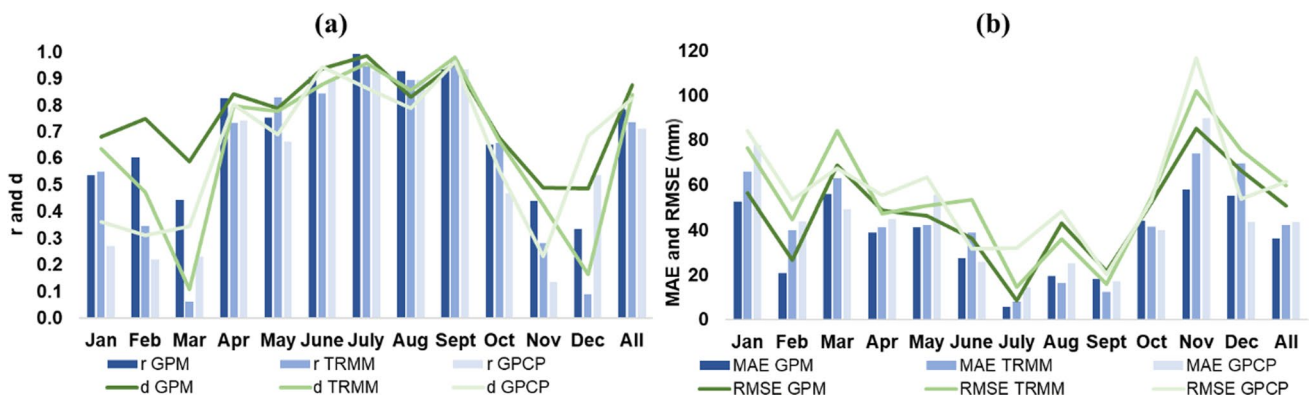


Fig. 3 Results of  $r$  and  $d$  (a) and MAE and RMSE (b) of GPM, TRMM and GPCP precipitation estimates in relation to precipitation data observed in surface on the monthly scale

in the Midwest of Brazil, Rozante et al. (2018) throughout Brazil and Su et al. (2019) in China. Furthermore, it is important to note that the GPM, TRMM and GPCP satellites estimated precipitation more accurately on the monthly scale than on the daily scale, as observed by Melo et al. (2015), Reis et al. (2017), Silva et al. (2019), Gadelha et al. (2019), Amorim et al. (2020) and Pedreira Junior et al. (2021) in Brazil. Huffman et al. (2007) asserts that better results are expected on a monthly time scale, because both IMERG and TMPA are corrected with surface precipitation data to remove monthly bias.

### 3.3 Seasonal analysis

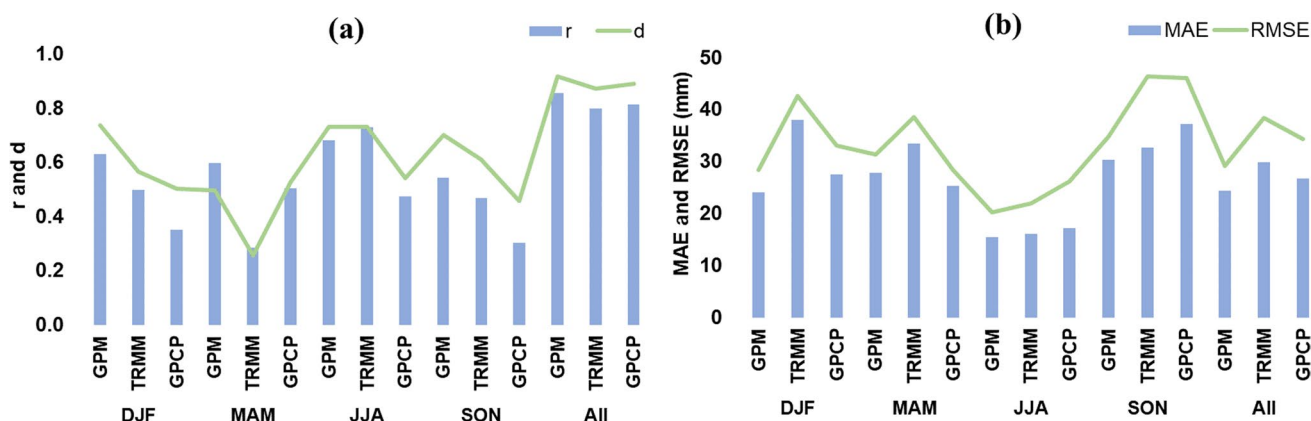
Figure 4 shows the results of  $r$ ,  $d$ , MAE and RMSE of the products of the GPM, TRMM and GPCP satellites in relation to the data observed on the surface on a seasonal scale: December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON) between the years 2012 and 2019. The GPM  $r$  ranged between 0.54 (SON) and 0.68 (JJA) with higher values for all periods compared to TRMM and GPCP, with the exception of TRMM in the JJA quarter ( $r=0.73$ ). As well as the GPM  $d$ , which varied between 0.50 (MAM) and 0.74 (DJF) with higher values for all periods compared to TRMM and GPCP, with the exception of TRMM in the JJA quarter ( $d=0.73$ ).

Regarding the MAE and RMSE, it is possible to highlight that the smallest errors occurred in the GPM estimates ( $15.48 \text{ mm} < \text{MAE} < 30.26 \text{ mm}$  and  $20.17 \text{ mm} < \text{RMSE} < 34.82 \text{ mm}$ ) in practically all analysed periods, with the exception of the GPCP in MAM (MAE = 25.27 mm and RMSE = 28.41 mm). The highest correlations/agreement and lowest errors between the estimated and observed datasets occurred in the JJA period, that is, the driest period in the Midwest Region of Brazil. On the other hand, the lowest correlations/agreements

and the highest errors between the data occurred in the other periods, especially SON and DJF, the rainiest periods in the study area. Although Reis et al. (2017) found higher values of  $r$  among the TRMM and observed data in the same quarters in the Southeast Region of Brazil ( $0.75 < r < 0.87$ ), there was a similar behaviour of the results, because the best performance of the TRMM data occurred in the JJA period and the worst in the SON and DJF periods, as observed by Saldanha et al. (2015) in a study carried out with GPCP data in South Brazil.

In the general context, when evaluating all quarters simultaneously from 2012 to 2019, the three groups of satellites obtained excellent performances in the results of the statistical indicators, especially the precipitation estimates from the GPM ( $r=0.85$ ,  $d=0.92$ , MAE = 24.41 mm and RMSE = 29.21 mm). This result reinforces the good ability of the GPM IMERG-F product to adequately capture the seasonality of precipitation (Gaona et al. 2016; Rozante et al. 2018; Rodrigues et al. 2021), as well as the TRMM TMPA (Reis et al. 2017) and GPCP MON (Saldanha et al. 2015; Torres et al. 2020) products in Brazil. However, when analysing the periods separately, there were some relatively inferior results, especially in periods with higher temperatures (Higgins et al. 2010; Saldanha et al. 2015). This can be explained by the formation of isolated convective systems (Saldanha et al. 2015) and warm clouds over the region studied during these periods, which in turn generate worse satellite precipitation estimates (Rodrigues et al. 2021).

Finally, from the seasonal statistical analyses, it is possible to infer that the increase in the time scale improves the performance of the precipitation estimates of the GPM, TRMM and GPCP satellites (Pedreira Junior et al. 2021). Table 1 shows the general results of the  $r$ ,  $d$ , MAE and RMSE indicators on the daily, monthly and seasonal scales of the three groups of satellites analysed. The values shown in bold represent the better performance and values in italic



**Fig. 4** Results of  $r$  and  $d$  (a) and MAE and RMSE (b) of the GPM, TRMM and GPCP precipitation estimates in relation to the precipitation data observed in surface in the seasonal scale



represents worse performance of that satellite when compared to the others, while the results in normal style symbolize intermediate performance or a tie with another satellite. In general, it is possible to conclude that the GPM estimates are more reliable than those of the TRMM and GPCP satellites in the municipality of Campo Grande, located in the Midwest Region of Brazil, as concluded by Pedreira Junior et al. (2021) in the state of Mato Grosso.

The limitation of this work is the use of a small study area compared to the entire municipality of Campo Grande and the state of MS. However, this is justifiable due to the lack of regularly distributed in situ gauges with consistent and reliable data both in Brazil and in this region, as reported by Gadelha et al. (2019). Almagro et al. (2021) highlight that although Brazil is one of the most important countries for global water flows, it has scarce allocation of resources for hydrometeorological monitoring, which results in major challenges for the adequate knowledge of its water resources, including precipitation. According to Xavier et al. (2016) and Gadelha et al. (2019), the density of in situ gauges in Brazil (1 per 720 km<sup>2</sup>) is below that recommended by the World Meteorological Organization (1 per 575 km<sup>2</sup>) (WMO 1994), mainly in the North and Midwest Regions (Curtarelli et al. 2014).

It is important to highlight that the urban area of Campo Grande has been suffering from an increase in hydrological disasters in recent years. In this scenario, Almagro et al. (2021) concluded that the use of precipitation products from satellites improves the ability to mitigate extreme hydrological events, such as floods and droughts. Therefore, the estimates of precipitation via remote sensing can be an alternative for future studies that aim to alert the population in relation to periods and rainfall volumes more susceptible

to flooding, as well as areas that require more mitigation actions on the part of the public administration, in order to minimize environmental, social and economic damage. Additionally, satellite-based precipitation products are valuable tools for data-poor regions due to their low latency and global reach, enabling continuous and high-quality monitoring of water resources (Almagro et al. 2021).

In this context, despite having been carried out outside the urban area and in a small study area, the present study sought to evaluate the performance of rainfall estimates from satellites based on available and reliable observed data close to the city, as a way of encourage the expansion of rainfall monitoring in the capital and state of MS, as well as contribute to future research with a larger study area. Finally, it is important to emphasize that one of the main advantages of using precipitation estimates via remote sensing is its temporal and spatial continuity (Melo et al. 2015). Nevertheless, it is necessary to continually update and expand the network of in situ gauges in Brazilian municipalities in order to assess the reliability of satellite products as recommended by Melo et al. (2015).

### 4 Conclusions

The objective of this study was to compare the performance of precipitation estimates based on remote sensing of the GPM, TRMM and GPCP in relation to the data observed by in situ gauges, in the daily, monthly and seasonal time scales, in the capital of the state of MS, Midwest Region of Brazil. On the daily scale, precipitation estimates by GPM and GPCP had similar performances and more satisfactory in relation to correlation, agreement, errors and detection of rainfall observed on the surface compared to TRMM estimates, with a slight advantage for GPCP estimates. Nevertheless, caution is needed before using daily precipitation data estimated via satellite, because no excellent statistical results were found, but moderate.

In monthly and seasonal scales, in general, the estimates from the IMERG-F product were more reliable than the estimates from the TMPA and GPCPMON products. Furthermore, it is possible to conclude that increasing the time scale considerably improves the correlation and agreement between the data estimated via remote sensing and those observed on the surface. Therefore, this study demonstrated that the estimates from the GPM, TRMM and GPCP satellites can be an alternative to the absence of surface precipitation measurements in a region close to the urban area of the municipality of Campo Grande-MS, especially the GPM estimates on longer time scales and drier periods.

In this way, it is expected that the results of this work will help in the planning of several socioeconomic activities that involve precipitation data, such as agriculture, livestock,

**Table 1** General results of *r*, *d*, MAE and RMSE of the GPM, TRMM and GPCP precipitation estimates in relation to the surface observed precipitation data in the daily, monthly and seasonal time scales

Scale	Satellite	<i>r</i>	<i>d</i>	MAE (mm)	RMSE (mm)
Daily	GPM	0.67	0.79	3.08	7.55
	TRMM	<i>0.62</i>	<i>0.76</i>	3.28	7.90
	GPCPDAY	0.67	0.79	<b>3.00</b>	<b>7.36</b>
Monthly	GPM	<b>0.78</b>	<b>0.88</b>	<b>36.01</b>	<b>50.79</b>
	TRMM	0.74	0.84	42.22	59.88
	GPCPMON	<i>0.71</i>	<i>0.82</i>	<i>43.43</i>	<i>61.49</i>
Seasonal	GPM	<b>0.85</b>	<b>0.92</b>	<b>24.41</b>	<b>29.21</b>
	TRMM	<i>0.80</i>	<i>0.87</i>	29.78	38.31
	GPCPMON	0.81	0.89	26.78	34.32

The values shown in bold represent the better performance and values in italic represents worse performance of the satellite when compared to the others, while the results in normal style symbolize intermediate performance or a tie with another satellite

energy generation and identification of risk areas for hydrological disasters in regions with climates characterized by dry winter and humid summer. Finally, it is recommended to increase the number of in situ gauges and decrease their respective percentages of sampling failures, in order to allow new spatially and temporally more representative assessments between the estimated and observed precipitation data in Brazil.

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**Data availability** Some of the data are publicly available and their references are provided in the manuscript. Other restricted data are available from the corresponding author upon reasonable request and with permission of the source department.

**Code availability** Not applicable.

## Declarations

**Ethical approval** Not applicable.

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## References

- Abreu M, Souza A, Lins TMP et al (2020) Comparison and validation of TRMM satellite precipitation estimates and data observed in Mato Grosso do Sul state, Brazil. *Rev Bras De Climatologia* 27:566–589. <https://doi.org/10.5380/abclima.v27i0.68569>
- Almagro A, Oliveira PTS, Brocca L (2021) Assessment of bottom-up satellite rainfall products on estimating river discharge and hydrologic signatures in Brazilian catchments. *J Hydrol* 603:126897. <https://doi.org/10.1016/j.jhydrol.2021.126897>
- Amorim JDS, Viola MR, Junqueira R, Oliveira VAD, Mello CRD (2020) Evaluation of satellite precipitation products for hydrological modeling in the Brazilian cerrado biome. *Water* 12(9):2571. <https://doi.org/10.3390/w12092571>
- Andrade JM, Neto AR, Bezerra UA, Moraes ACC, Montenegro SMGL (2022) A comprehensive assessment of precipitation products: temporal and spatial analyses over terrestrial biomes in Northeastern Brazil. *Remote Sens Appl: Soc Environ* 28:100842. <https://doi.org/10.1016/j.rsase.2022.100842>
- Araujo Palharini RS, Vila DA, Rodrigues DT et al (2021) Assessment of extreme rainfall estimates from satellite-based: regional analysis. *Remote Sens Appl: Soc Environ* 23:100603. <https://doi.org/10.1016/j.rsase.2021.100603>
- Bosilovich MG, Robertson FR, Takacs L, Molod A, Mocko D (2017) Atmospheric water balance and variability in the MERRA-2 reanalysis. *J Clim* 30(4):1177–1196. <https://doi.org/10.1175/JCLI-D-16-0338.1>
- Brasil Neto RM, Guimaraes Santos CA, Marques da Silva R, Costa dos Santos CA (2022) Evaluation of TRMM satellite dataset for monitoring meteorological drought in Northeastern Brazil. *Hydrol Sci J* 67(14):2100–2120. <https://doi.org/10.1080/02626667.2022.2130333>
- Cavalcante RBL, da Silva Ferreira DB, Pontes PRM, Tedeschi RG, da Costa CPW, de Souza EB (2020) Evaluation of extreme rainfall indices from CHIRPS precipitation estimates over the Brazilian Amazonia. *Atmos Res* 238:104879. <https://doi.org/10.1016/j.atmosres.2020.104879>
- Chen C, Chen Q, Duan Z, Zhang J, Mo K, Li Z, Tang G (2018) Multi-scale comparative evaluation of the GPM IMERG v5 and TRMM 3B42 v7 precipitation products from 2015 to 2017 over a climate transition area of China. *Remote Sensing* 10(6):944. <https://doi.org/10.3390/rs10060944>
- Curtarelli MP, Rennó CD, Alcântara EH (2014) Evaluation of the tropical rainfall measuring mission 3B43 product over an inland area in Brazil and the effects of satellite boost on rainfall estimates. *J Appl Remote Sens* 8(1):083589–083589. <https://doi.org/10.1117/1.JRS.8.083589>
- Duan Z, Liu J, Tuo Y, Chiogna G, Disse M (2016) Evaluation of eight high spatial resolution gridded precipitation products in Adige Basin (Italy) at multiple temporal and spatial scales. *Sci Total Environ* 573:1536–1553. <https://doi.org/10.1016/j.scitotenv.2016.08.213>
- Ebert EE, Janowiak JE, Kidd C (2007) Comparison of near-real-time precipitation estimates from satellite observations and numerical models. *Bull Am Meteor Soc* 88(1):47–64. <https://doi.org/10.1175/BAMS-88-1-47>
- Feitosa JRM, Oliveira CW (2020) Estudo comparativo dos dados de precipitação do satélite TRMM e postos pluviométricos no estado do Ceará, Brasil. *Revista Geografica de América Central* (65):239–262. <https://doi.org/10.15359/rgac.65-2.10>
- Ferguson CR, Wood EF, Vinukollu RK (2012) A global intercomparison of modeled and observed land-atmosphere coupling. *J Hydrometeorol* 13(3):749–784. <https://doi.org/10.1175/JHM-D-11-0119.1>
- Franchito SH, Rao VB, Vasques AC, Santo CME, Conforte JC (2009) Validation of TRMM precipitation radar monthly rainfall estimates over Brazil. *J Geophys Res Atmos*: 114(D2):1–9. <https://doi.org/10.1029/2007JD009580>
- Gadelha AN, Coelho VHR, Xavier AC et al (2019) Grid box-level evaluation of IMERG over Brazil at various space and time scales. *Atmos Res* 218:231–244. <https://doi.org/10.1016/j.atmosres.2018.12.001>
- Gaona MR, Overeem A, Leijnse H, Uijlenhoet R (2016) First-year evaluation of GPM rainfall over the Netherlands: IMERG day 1 final run (V03D). *J Hydrometeorol* 17(11):2799–2814. <https://doi.org/10.1175/JHM-D-16-0087.1>
- Higgins RW, Kousky VE, Silva VBS, Becker E, Xie P (2010) Intercomparison of daily precipitation statistics over the United States in observations and in NCEP reanalysis products. *J Clim* 23(17):4637–4650. <https://doi.org/10.1175/2010JCLI3638.1>

- Hinkle DE, Wiersma W, Jurs SG (2003) Applied statistics for the behavioral sciences. Houghton Mifflin, USA
- Hofstra N, Haylock M, New M, Jones P, Frei C (2008) Comparison of six methods for the interpolation of daily, European climate data. *J Geophys Res: Atmos* 113(D21). <https://doi.org/10.1029/2008JD010100>
- Hosseini-Moghari SM, Tang Q (2020) Validation of GPM IMERG V05 and V06 precipitation products over Iran. *J Hydrometeorol* 21(5):1011–1037. <https://doi.org/10.1175/JHM-D-19-0269.1>
- Hou AY, Kakar RK, Neeck S et al (2014) The global precipitation measurement mission. *Bull Am Meteor Soc* 95(5):701–722. <https://doi.org/10.1175/BAMS-D-13-00164.1>
- Hu Q, Yang D, Li Z, Mishra AK, Wang Y, Yang H (2014) Multi-scale evaluation of six high-resolution satellite monthly rainfall estimates over a humid region in China with dense rain gauges. *Int J Remote Sens* 35(4):1272–1294. <https://doi.org/10.1080/01431161.2013.876118>
- Huffman GJ, Bolvin DT, Nelkin EJ et al (2007) The TRMM multisatellite precipitation analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J Hydrometeorol* 8(1):38–55. <https://doi.org/10.1175/JHM560.1>
- Huffman GJD, Bolvin DT, Braithwaite D et al (2015) NASA global precipitation measurement (GPM) integrated multi-satellite retrievals for GPM (IMERG). [https://gpm.nasa.gov/sites/default/files/2020-05/IMERG\\_ATBD\\_V06.3.pdf](https://gpm.nasa.gov/sites/default/files/2020-05/IMERG_ATBD_V06.3.pdf). Accessed 10 June 2022
- IBGE (2021) Data from the municipality of Campo Grande - MS. Brazilian Institute of Geography and Statistics. Campo Grande, Brazil. <https://www.ibge.gov.br/cidades-e-estados/ms/campo-grande.html>. Accessed 10 June 2022
- Katsanos D, Retalis A, Michaelides S (2016) Validation of a high-resolution precipitation database (CHIRPS) over Cyprus for a 30-year period. *Atmos Res* 169:459–464. <https://doi.org/10.1016/j.atmosres.2015.05.015>
- Khandu AJL, Forootan E (2016) An evaluation of high-resolution gridded precipitation products over Bhutan (1998–2012). *Int J Climatol* 36(3):1067–1087. <https://doi.org/10.1002/joc.4402>
- Khodadoust Siuki S, Saghafian B, Moazami S (2017) Comprehensive evaluation of 3-hourly TRMM and half-hourly GPM-IMERG satellite precipitation products. *Int J Remote Sens* 38(2):558–571. <https://doi.org/10.1080/01431161.2016.1268735>
- Kim K, Park J, Baik J, Choi M (2017) Evaluation of topographical and seasonal feature using GPM IMERG and TRMM 3B42 over Far-East Asia. *Atmos Res* 187:95–105. <https://doi.org/10.1016/j.atmosres.2016.12.007>
- Le MH, Lakshmi V, Bolten J, Du Bui D (2020) Adequacy of satellite-derived precipitation estimate for hydrological modeling in Vietnam Basins. *J Hydrol* 586:124820. <https://doi.org/10.1016/j.jhydrol.2020.124820>
- Liu J, Duan Z, Jiang J, Zhu A (2015) Evaluation of three satellite precipitation products TRMM 3B42, CMORPH, and PERSIANN over a subtropical watershed in China. *Adv Meteorol* 2015. <https://doi.org/10.1155/2015/151239>
- Lockhoff M, Zolina O, Simmer C, Schulz J (2014) Evaluation of satellite-retrieved extreme precipitation over Europe using gauge observations. *J Clim* 27(2):607–623. <https://doi.org/10.1175/JCLI-D-13-00194.1>
- López-Bermeo C, Montoya RD, Caro-Lopera FJ, Díaz-García JA (2022) Validation of the accuracy of the CHIRPS precipitation dataset at representing climate variability in a tropical mountainous region of South America. *Phys Chem Earth, Parts A/B/C* 127:103184. <https://doi.org/10.1016/j.pce.2022.103184>
- Melo DDC, Xavier AC, Bianchi T, Oliveira PT, Scanlon BR, Lucas MC, Wendland E (2015) Performance evaluation of rainfall estimates by TRMM multi-satellite precipitation analysis 3B42V6 and V7 over Brazil. *J Geophys Res: Atmos* 120(18):9426–9436. <https://doi.org/10.1002/2015JD023797>
- Moraes RBFD, Gonçalves FV (2021) Validation of TRMM data in the geographical regions of Brazil. *RBRH* 36(26):1–14. <https://doi.org/10.1590/2318-0331.262120210071>
- Oliveira-Júnior JF, Silva Junior CA, Teodoro PE et al (2021) Confronting CHIRPS dataset and in situ stations in the detection of wet and drought conditions in the Brazilian Midwest. *Int J Climatol* 41(9):4478–4493. <https://doi.org/10.1002/joc.7080>
- Paredes-Trejo FJ, Barbosa HA, Kumar TL (2017) Validating CHIRPS-based satellite precipitation estimates in Northeast Brazil. *J Arid Environ* 139:26–40. <https://doi.org/10.1016/j.jaridenv.2016.12.009>
- Paredes-Trejo F, Barbosa H, dos Santos CAC (2019) Evaluation of the performance of SM2RAIN-derived rainfall products over Brazil. *Remote Sensing* 11(9):1–28. <https://doi.org/10.3390/rs11091113>
- Pedreira Junior AL, Biudes MS, Machado NG et al (2021) Assessment of remote sensing and re-analysis estimates of regional precipitation over Mato Grosso, Brazil. *Water* 13(3):333. <https://doi.org/10.3390/w13030333>
- Pessi DD, dos Santos CSA, Nonato JJ et al (2019) Validation of the monitors of the TRMM soil satellite in the state of Mato Grosso Brazil. *Rev de Ciências Agrárias (Portugal)* 42(1):79–88. <https://doi.org/10.19084/RCA18217>
- PLANURB (2021) Socioeconomic profile of Campo Grande. 28° ed. Campo Grande
- Prakash S, Mitra AK, Aghakouchak A, Liu Z, Norouzi H, Pai DAS (2018) A preliminary assessment of GPM-based multi-satellite precipitation estimates over a monsoon dominated region. *J Hydrol* 556:865–876. <https://doi.org/10.1016/j.jhydrol.2016.01.029>
- QGIS (2022) Geographic Information System version 3.22.5. QGIS Association. <http://www.qgis.org>
- Reis JBC, Rennó CD, Lopes ESS (2017) Validation of satellite rainfall products over a mountainous watershed in a humid subtropical climate region of Brazil. *Remote Sensing* 9(12):1240. <https://doi.org/10.3390/rs9121240>
- Rodrigues DT, Gonçalves WA, Spyrides MHC, Santos e Silva CM (2020) Spatial and temporal assessment of the extreme and daily precipitation of the tropical rainfall measuring mission satellite in Northeast Brazil. *Int J Remote Sensing* 41(2):549–572. <https://doi.org/10.1080/01431161.2019.1643940>
- Rodrigues DT, Gonçalves WA, Spyrides MHC, Santos e Silva CM, de Souza DO (2020) Spatial distribution of the level of return of extreme precipitation events in Northeast Brazil. *Int J Climatol* 40(12):5098–5113. <https://doi.org/10.1002/joc.6507>
- Rodrigues DT, Santos e Silva CM, dos Reis JS et al (2021) Evaluation of the integrated multi-satellite retrievals for the global precipitation measurement (IMERG) product in the São Francisco basin (Brazil). *Water* 13(19):2714. <https://doi.org/10.3390/w13192714>
- Rozante JR, Vila DA, Barboza Chiquetto J, Fernandes ADA, Souza Alvim D (2018) Evaluation of TRMM/GPM blended daily products over Brazil. *Remote Sensing* 10(6):882. <https://doi.org/10.3390/rs10060882>
- Sahlu D, Nikolopoulos EI, Moges SA, Anagnostou EN, Hailu D (2016) First evaluation of the Day-1 IMERG over the upper Blue Nile basin. *J Hydrometeorol* 17(11):2875–2882. <https://doi.org/10.1175/JHM-D-15-0230.1>
- Saldanha CB, Radin B, Cardoso MAG et al (2015) Comparação dos dados de precipitação gerados pelo GPCP vs observados para o estado do Rio Grande do Sul. *Rev Bras De Meteorol* 30:415–422. <https://doi.org/10.1590/0102-778620140139>
- Salles L, Satgé F, Roig H et al (2019) Seasonal effect on spatial and temporal consistency of the new GPM-based IMERG-v5 and GSMaP-v7 satellite precipitation estimates in Brazil's Central Plateau region. *Water* 11(4):668. <https://doi.org/10.3390/w11040668>

- Sharifi E, Steinacker R, Saghaflian B (2016) Assessment of GPM-IMERG and other precipitation products against gauge data under different topographic and climatic conditions in Iran: Preliminary results. *Remote Sensing* 8(2):135. <https://doi.org/10.3390/rs8020135>
- Silva CB, Silva MES, Ambrizzi T et al (2019) Precipitação na América do Sul—dados obtidos por estações meteorológicas automáticas e por sistemas orbitais. *Rev Bras de Climatol* 25:1–26. <https://doi.org/10.5380/abclima.v25i0.58813>
- Singh R, Shekhar M, Pandey VK, Kumar R, Sharma RK (2018) Causes and geomorphological effects of large debris flows in the lower valley areas of the meru and gangotri glaciers, Bhagirathi basin, Garhwal Himalaya (India). *Remote Sensing Lett* 9(8):809–818. <https://doi.org/10.1080/2150704X.2018.1484956>
- Singh N, Kumar A, Anshumali Singh J, Nath D (2020) Observations on the distribution of precipitation over northern India using joint CloudSat, CALIPSO and TRMM measurements. *Remote Sensing Lett* 11(2):117–126. <https://doi.org/10.1080/2150704X.2019.1692388>
- Su J, Lü H, Ryu D, Zhu Y (2019) The assessment and comparison of TMPA and IMERG products over the major basins of Mainland China. *Earth Space Sci* 6(12):2461–2479. <https://doi.org/10.1029/2019EA000977>
- Sun Q, Miao C, Duan Q, Ashouri H, Sorooshian S, Hsu KL (2018) A review of global precipitation data sets: data sources, estimation, and intercomparisons. *Rev Geophys* 56(1):79–107. <https://doi.org/10.1002/2017RG000574>
- Tan ML, Santo H (2018) Comparison of GPM IMERG, TMPA 3B42 and PERSIANN-CDR satellite precipitation products over Malaysia. *Atmos Res* 202:63–76. <https://doi.org/10.1016/j.atmosres.2017.11.006>
- Tang G, Behrangi A, Long D, Li C, Hong Y (2018) Accounting for spatiotemporal errors of gauges: a critical step to evaluate gridded precipitation products. *J Hydrol* 559:294–306. <https://doi.org/10.1016/j.jhydrol.2018.02.057>
- Thiemig V, Rojas R, Zambrano-Bigiarini M, Roo A (2013) Hydrological evaluation of satellite-based rainfall estimates over the Volta and Baro-Akobo Basin. *J Hydrol* 499:324–338. <https://doi.org/10.1016/j.jhydrol.2013.07.012>
- Tian Y, Peters-Lidard CD, Adler RF, Kubota T, Ushio T (2010) Evaluation of GSMaP precipitation estimates over the contiguous United States. *J Hydrometeorol* 11(2):566–574. <https://doi.org/10.1175/2009JHM1190.1>
- Torres F, Kuki C, Ferreira G et al (2020) Validação de Diferentes Bases de Dados de Precipitação nas Bacias Hidrográficas do Sapucaí e São Francisco. *Rev Bras de Climatol* 27. <https://doi.org/10.5380/abclima.v27i0.73634>
- Wang Z, Zhong R, Lai C, Chen J (2017a) Evaluation of the GPM IMERG satellite-based precipitation products and the hydrological utility. *Atmos Res* 196:151–163
- Wang W, Lu H, Zhao T, Jiang L, Shi J (2017b) Evaluation and comparison of daily rainfall from latest GPM and TRMM products over the Mekong River Basin. *IEEE J Sel Top Appl Earth Obs Remote Sens* 10(6):2540–2549. <https://doi.org/10.1109/JSTARS.2017.2672786>
- Wang K, Kong L, Yang Z et al (2021) GPM annual and daily precipitation data for real-time short-term nowcasting: a pilot study for a way forward in data assimilation. *Water* 13(10):1422. <https://doi.org/10.3390/w13101422>
- Wilks DS (2011) *Statistical methods in the atmospheric sciences*, 3rd edn. Academic Press, Cambridge
- Willmott CJ (1981) On the validation of models. *Phys Geogr* 2:184–194
- WMO (1994) *Guide to hydrological practices: data acquisition and processing, analysis, forecasting and other applications*, 5th edn. Switzerland, Geneva
- Xavier AC, King CW, Scanlon BR (2016) Daily gridded meteorological variables in Brazil (1980–2013). *Int J Climatol* 36(6):2644–2659. <https://doi.org/10.1002/joc.4518>
- Xie P, Xiong AY (2011) A conceptual model for constructing high-resolution gauge-satellite merged precipitation analyses. *J Geophys Res: Atmos* 116(D21). <https://doi.org/10.1029/2011JD016118>
- Xu J, Ma Z, Yan S, Peng J (2022) Do ERA5 and ERA5-land precipitation estimates outperform satellite-based precipitation products? A comprehensive comparison between state-of-the-art model-based and satellite-based precipitation products over mainland China. *J Hydrol* 605:127353. <https://doi.org/10.1016/j.jhydrol.2021.127353>
- Yong B, Ren LL, Hong Y et al (2010) Hydrologic evaluation of multi-satellite precipitation analysis standard precipitation products in basins beyond its inclined latitude band: a case study in Laohahe basin, China. *Water Resour Res* 46(7):1–20. <https://doi.org/10.1029/2009WR008965>
- Yu C, Zheng J, Hu D et al (2021) Evaluation and correction of IMERG late run precipitation product in rainstorm over the southern basin of China. *Water* 13(2):231. <https://doi.org/10.3390/w13020231>

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