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Evaluation of the IMERG Product in the MATOPIBA Region, Brazil

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Abstract: Managing water resources around the world requires challenges imposed by natural and anthropogenic processes. Having knowledge about water resources, whether qualitative or quantitative, almost always depends on monitoring rainfall stations for their temporal and spatial understanding. Monitoring dry and wet seasons in a country or region is a difficult problem, especially when the network of meteorological stations is sparse or does not cover the entire area. The Integrated Multisatellite Retrieval of Global Precipitation Measurements (IMERG) produces and provides a source of high-resolution spatial and temporal precipitation estimates obtained by satellites and has been widely used since its launch in 2014, providing global precipitation data since 2000. In the present study, the performance of the GPM (Global Precipitation Measurement) product (IMERG-final run) was evaluated in the MATOPIBA region, located in the northern and northeastern regions of Brazil, from October 2000 to September 2021. The monthly and annual IMERG estimates were compared against the rainfall data from 197 ground stations in the study region belonging to the Agência Nacional das Águas (ANA). The metrics used for this study's analysis of IMERG's performance in detecting rainfall were both quantitative and qualitative. The IMERG estimates overestimated those of the rain gauges by about 13%. However, the performance result was quite satisfactory for the estimation of rainfall events, both monthly and annually, that is, excellent correlation with their spatial and temporal distribution as well as their volume. It was concluded that this product is a satisfactory source of alternative rainfall data, especially in areas without a dense network of rain gauges, such as the study region.

Keywords: Rainfall, GPM, Satellite Products

I. INTRODUCTION

Rainfall is one of the main mechanisms of the hydrological cycle; it connects the surface-ocean-atmosphere movement, and commands the conditions of agricultural activities, water storage and supply, and the prediction, and detection of natural disasters and extreme weather conditions. Due to the influence of atmospheric dynamics and environmental factors, rainfall presents great spatial-temporal and intensity variability. Monitoring rainfall is essential for making various technical and policy decisions, as well as for mitigating and adapting to climate change, allowing the magnitude of these changes to be quantified [1].

The water cycle describes the continuous movement of water above and below the Earth's surface. Rainfall is widely recognized as the main "engine" of this global cycle and plays a fundamental role in regulating the climate system [2]. Estimating rainfall over large areas is important for a complete understanding of water availability, influences society's decision-making, and is also a source of data for scientific models [3].

Several cities in Brazil and around the world have been facing problems related to the scarcity of information regarding water. Floods, droughts, and the degradation of water bodies are cited, mainly due to the lack of financial investments from the State for adaptations and adjustments of infrastructure scenarios in relation to available water resources [4].

Meteorological observations are essential to characterising precipitation and provide references for current (short-term) and climate (long-term) weather forecasting models. Measuring rainfall worldwide from a terrestrial perspective is a challenge, as rain gauges that provide current rainfall values cover an area equal to or less than half a football field. The surface area of all rain gauges in operation worldwide is small, only 593×10^{-12} percent of the Earth's surface. Although there are considered to be numerous gauges, the actual amount of available equipment for the user varies greatly depending on the study time and latency requirements. The Global Centre for Precipitation Climatology (GPCC) pluviometric dataset is the most comprehensive currently available, containing about 65.000 gauges. However, since the equipment represents only the actual position of a point, it is concluded that most of the Earth's surface remains uncovered. Even if each GPCC station represented an extended area of 5 km^2 from each gauge (assuming they did not overlap), this would still be only about 1% of the Earth's surface [5].

The Intergovernmental Panel on Climate Change (IPCC) shows that rainfall metric patterns are changing in many parts of the planet, with signs of increased extreme events such as droughts and floods. In north-eastern South America, extreme rainfall is expected to increase in intensity and frequency, as well as the duration of dry periods [6].

Satellite observations have been useful in analysing trends in these extreme events and other factors that influence changes in land use. Most applications of these studies use multi-satellite pluviometric products. These products use algorithms to combine the international constellation of passive microwave sensors from the Global Precipitation Measurement (GPM) mission and Infrared (IR) measurement based on geostationary satellites, and can also integrate rain gauge information [7].

IMERG version 6 operates with a spatial resolution of 0.1° × 0.1°, and a temporal resolution of 30 min, and a spatial coverage between 60° N and 60° S. IMERG precipitation estimates are calculated by the Goddard Profiling Algorithm [8], using measurements from passive microwave sensors, calibrated against GPM microwave radar estimates and merged into half-hour estimates. These estimates are then recalibrated with the CMORPH Kalman Filter (CMORPH-KF) and the PERSIANN Cloud Classification System. After bias correction with monthly rain gauge measurements, the final IMERG precipitation product is obtained [9].

In almost 30 years of observations, satellite data has emerged as a promising source of precipitation observations on a global scale [10]. A respectable number of studies evaluating the performance of IMERG precipitation products at various temporal and spatial scales around the globe can be found in the literature[11–22]. In studies conducted globally, [23]gathered articles on IMERG calibration worldwide. However, since IMERG products have only recently become available, the number of studies conducted in Brazil from local to national scale is still very small.

The GPM Mission provides several Integrated Multi-satellite Retrievals for GPM (IMERG) products that are designed to intercalibrate, merge, and interpolate microwave and rain gauge data for precipitation estimation. IMERG version 6 is divided into three categories based on delay and accuracy: IMERG-Early run (IMERG-E), IMERG-Late run (IMERG-L), and IMERG-final run (IMERG-F). IMERG-E, with a delay of 4 hours, is suitable for near-real-time flash flood forecasting. IMERG-L, with a delay of 12 hours, is suitable for water management and other purposes; these two products are defined as near-real-time multi-satellite products. IMERG-F, calibrated with a delay of 3.5 months, is suitable for post-processing and data research and is defined as a real-time satellite measurement product [24].

According to the World Bank, agriculture has ties to several sectors of the economy, so if agricultural income was used for products and services, there would be a stimulation of the industrial and tertiary sectors [25]. In the region known as MATOPIBA, grain production is expected to increase from 31.8 million tons in 2021/2022 to 40.2 million tons in the next 10 years, on a planted area of 10.3 million hectares in 2031/32 [26].

There are about 324 thousand agricultural establishments, 46 conservation units, 35 indigenous lands. and 781 agrarian reform settlements in the region. MATOPIBA is composed of scenarios of great diversity and complexity, covering social issues such as the coexistence of agribusiness and family agriculture in the same territory, preservation areas, indigenous and *quilombola* areas, as well as issues related to soil and climate characteristics that define the region [27].

Given the global importance of the region for food security, the aim of this study was to evaluate the performance of rainfall data from the GPM-IMERG product (version 6 - final run) on a monthly and annual basis (from October 2000 to September 2021) for the MATOPIBA region.

II. MATERIALS AND METHODS

The research was conducted in the region known as MATOPIBA (an acronym for the states of Maranhão, Tocantins, Piauí and Bahia) (Figure 1 and Table 1). The climate is humid tropical with a dry winter (Aw), according to the Köppen-Geiger classification, with monthly mean temperatures between 25 and 27 °C throughout the year, and an annual mean rainfall ranging from 800 to 2000 mm, distributed in two seasons: the dry season, from May to September, and the rainy season, from October to April[28]. The territorial delimitation of this region was officially established by Federal Decree No. 8.447 of May 6, 2015, which provided for the Agricultural Development Plan (PDA), also creating the MATOPIBA Regional Development Agency by the *Ministério da Agricultura, Pecuária e Abastecimento*, as well as the Strategic Intelligence Group (Gite), an institution responsible for managing the PDA, which is linked to the *Empresa Brasileira de Pesquisa Agropecuária* (Embrapa).

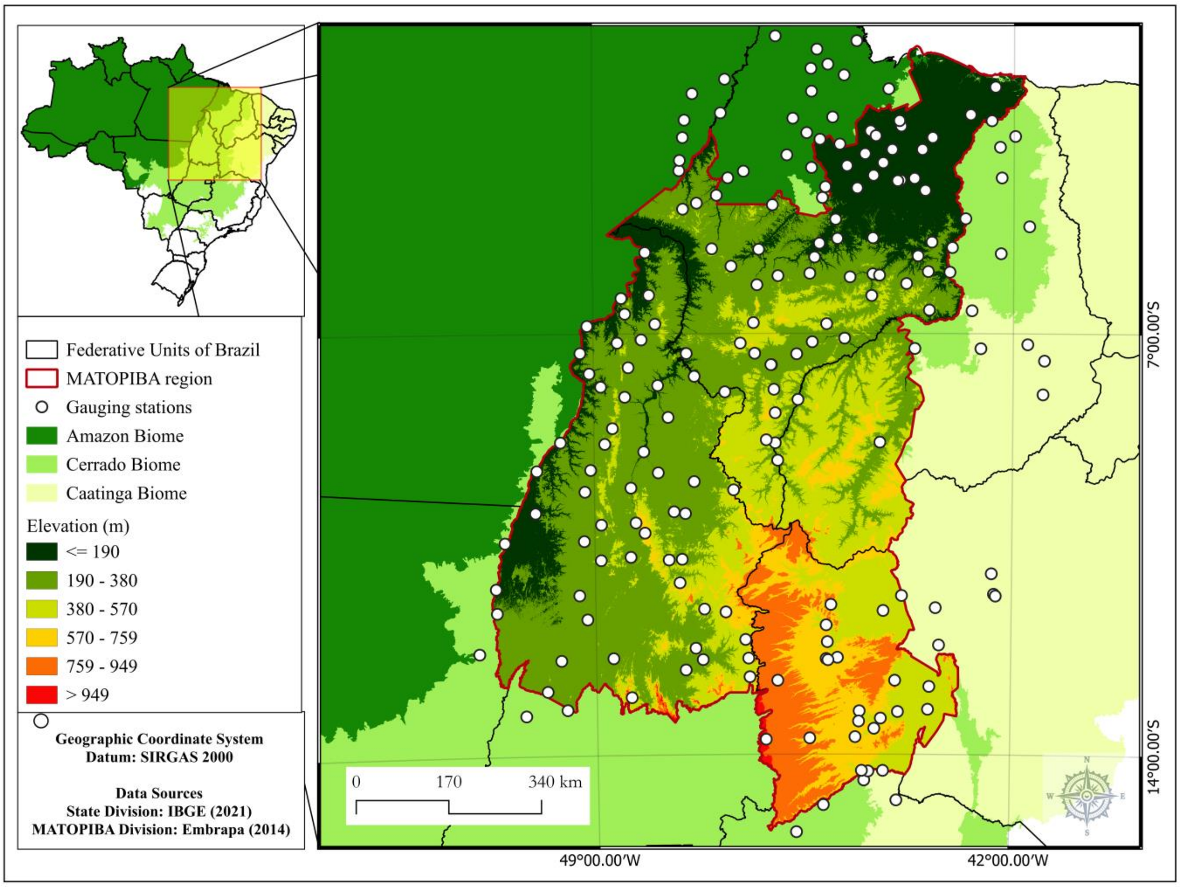


Fig. 1. Location of the study area and the rain gauges used to validate IMERG estimates in the MATOPIBA region.

Table 1 Characterization of the MATOPIBA region.

MATOPIBA				
State	**Microregions**	**Number of Municipalities**	**Area (Km^2)**	**Percentage (%)**
Maranhão	15	135	239.823	32,78
Tocantins	8	139	277.424	37,95
Piauí	4	33	82.046	11,21
Bahia	4	30	132.145	18,06
Total	**31**	**337**	**731.438**	**100**

Source: Elaborated with Gite data from Embrapa [29]

2.1 Observed data – (rain gauges)

The rainfall data was obtained from 197 stations of the pluviometric network of the National Water Agency and Basic Sanitation (ANA). The precipitation data was used for analysis on a monthly and annual scale, and the analysed series covered the period from October 2000 to September 2021 (21 hydrological years).

2.2 Estimated data – (satellite-IMERG)

The rainfall data from the Global Precipitation Measurement (GPM) mission's satellite constellation, IMERG Version 6, with a spatial-temporal resolution of 0.1º, were acquired from the Goddard Earth Sciences Data and Information Services Centre Distributed Active Archive Centre (GES DISC DAAC). Monthly and annual products were used, covering the period from October 2000 to September 2021, which coincides with the ground-based rain gauge network of ANA over the MATOPIBA region, as a reference. Additionally, Digital Elevation Model (DEM - 30 m) data was obtained from the USGS/NASA SRTM data.

2.3 Performance of the estimates

The quantitative evaluations of the estimates in the study were: correlation coefficient (CC), coefficient of determination (R^2), mean error (MBE), mean absolute error (MAE), and classification performance metrics: probability of detection (POD), false alarm rate (FAR), and critical success index (CSI). POD indicates the proportion of rainfall events correctly detected by satellites in relation to the total number of events detected; FAR measures the proportion of false events in the total number of events detected by satellites; and CSI indicates the proportion of rainfall events correctly detected by satellites in relation to the total number of observed events. These metrics have been used in several studies to assess the performance of satellite products[30–33]. The equations for the metrics used are presented in Table 2.

Table 2 Parameters calculated for evaluating the performance of IMERG.

Index	Equation	Unit	Best value
Correlation coefficient (CC)	$CC = \frac{\sum_{i=1}^{n}(Pi-\bar{P})(Oi-\bar{O})}{\sqrt{\sum_{i=1}^{n}(Pi-\bar{P})^2}\sqrt{\sum_{i=1}^{n}(Oi-\bar{O})^2}}$	-	1
Determination coefficient (R^2)	$R^2 = \frac{\{\sum_{i=1}^{n}(Pi-\bar{P})(Oi-\bar{O})\}^2}{\sum_{i=1}^{n}(Pi-\bar{P})^2\sum_{i=1}^{n}(Oi-\bar{O})^2}$	-	1
Mean error (MBE)	$MBE = \frac{1}{n}\sum_{i=1}^{n}(Pi-Oi)$	mm	0
Mean absolute error (MAE)	$MAE = \frac{1}{n}\sum_{i=1}^{n}\lvert Pi-Oi\rvert$	mm	0
Root of the mean square error (RMSE)	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Pi-Oi)^2}$	mm	0
Probability of detection (POD)	$POD = \frac{Hits}{Hits+Misses}$	-	1
Critical success index (CSI)	$\mathrm{CSI} = \frac{Hits}{Hits+FalseAlarm+Misses}$	-	1
False alarm ratio (RAF)	$\mathrm{RAF} = \frac{FalseAlarm}{Hits+FalseAlarm}$	-	0

Where: Oi are the observed data from ground-based rain gauges of an order *i*; Pi is the estimated order data (IMERG) of an order *i*; Hits are the days when both IMERG and rain gauges recorded rainfall; False Alarm are the days when IMERG recorded rainfall, but the rain gauges did not; Misses are the days when IMERG did not record rainfall, but the rain gauges did.

III. RESULTS AND DISCUSSION

Figure 2 shows the scatter plots of the precipitated product from the IMERG satellite versus the ground-based rain gauge data, on monthly and annual scales, from October 2000 to September 2021 over the MATOPIBA region. The evaluation metrics are also included in Figure 2. The satellite-based rainfall product showed high accuracy on the monthly scale with R^2=0.81 and on the annual scale with R^2=0.71.[34]evaluated the contribution of rain gauges in calibrating the IMERG product and obtained satisfactory precipitation estimates with R^2 = 0.80 in a first validation study in Spain.

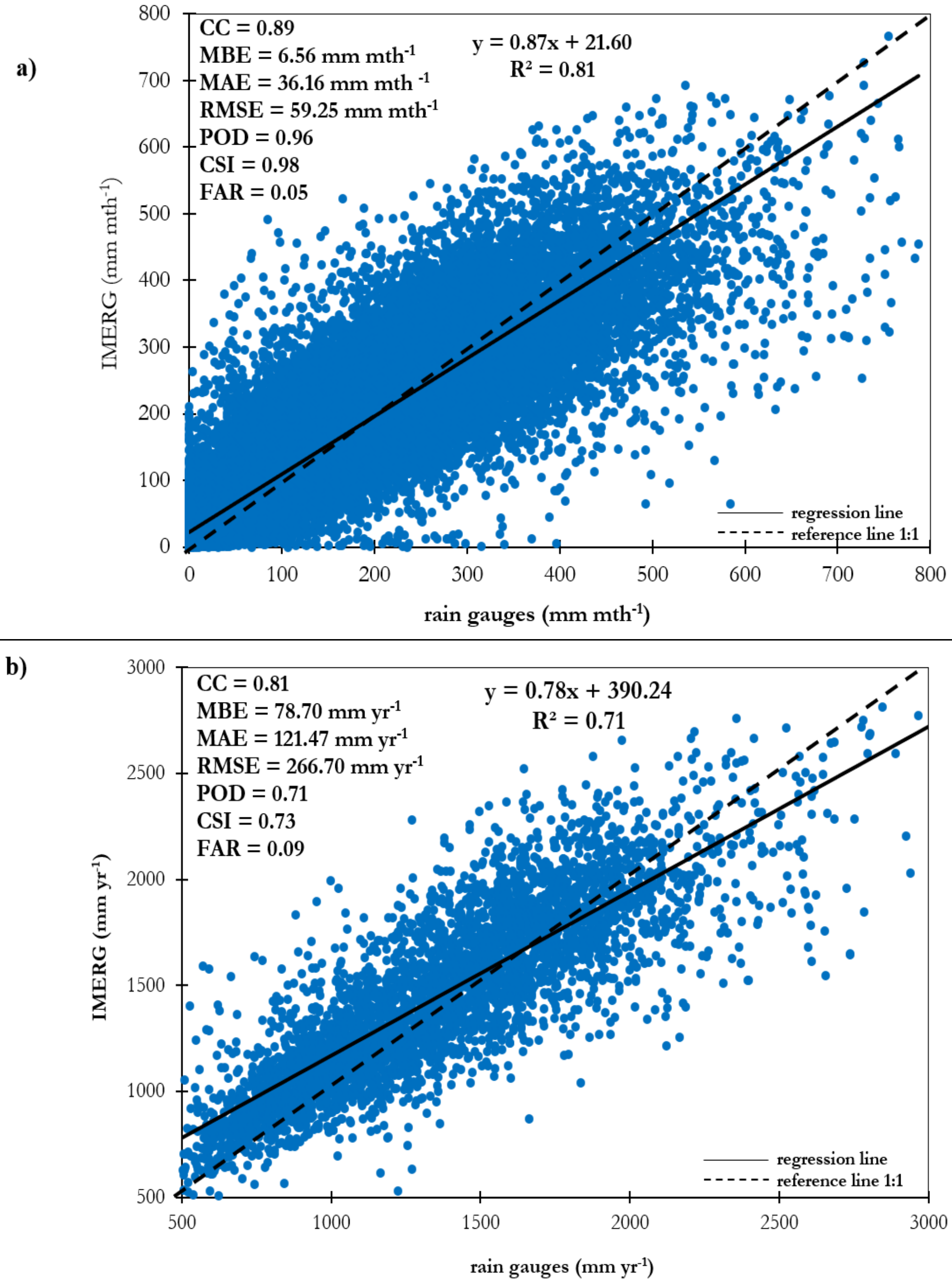


Fig. 2 Rainfall scatter plots of IMERG versus rain gauges. a) scatter plot of monthly values, b) scatter plot of annual values.

Quantitatively, scatter plots show that IMERG tends to overestimate accumulated precipitation, especially on an annual scale. However, IMERG performs well with a high correlation coefficient (0.89 ~ 0.81), RMSE (59.25 ~ 266.70), and MAE (36.16 ~ 121.47) on monthly and annual scales, respectively.[35]obtained a good estimate for the state of Ceará using TRMM satellite imagery, with an MAE value of 16.46 mm on average, a RMSE of 26.78 mm, and a correlation of 0.96.

[36] Comparing the daily and monthly rainfall estimates of the 3B42V7 product with the estimates from both IMERG products, obtained good overall agreement with reference data at both temporal scales. Both IMERG products showed significant superiority in terms of CC and RMSE.

[37] Conducted a study to preliminarily evaluate the GPM-IMERG's intra-seasonal rainfall estimates in three climatic zones (Japan, Nepal, and the Philippines) to test its ability to detect light/heavy rainfall events.

The authors concluded that the overall performance of GPM-IMERG reproduced the statistical characteristics of the monthly mean rainfall well. The RMSE and correlation were satisfactory, except for a severe underestimation of rainfall. On the other hand,[38] found that the estimated values of IMERG were higher than AIMERG and ground observations, resulting in IMERG's overestimation of up to 10 times that of AIMERG and ground observations in the territories of China.

Therefore, the positive merits of the propagation algorithm used in the IMERG Final Run process are confirmed. In studies conducted by [39]in southern China to capture extreme rainfall events using IMERG products, the authors highlighted that the product captured the space-time variability of rainfall with moderate to high CC's (0.6 to 0.87) for most events, and RMSE ranging from 31.58 mm to 47.50 mm on a monthly scale.

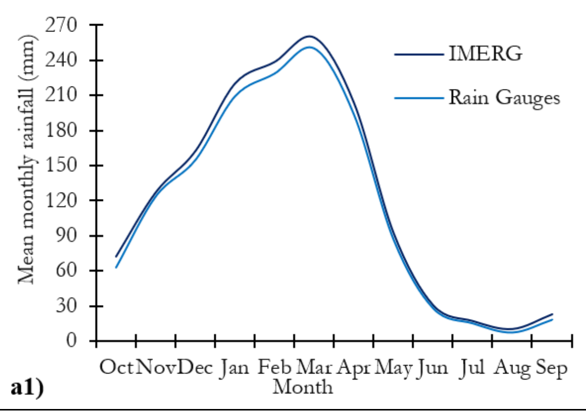
In this study, IMERG was able to capture the temporal variation of rainfall with observations of events with CC > 0.7. The distribution of POD, CSI, and FAR showed a good performance of IMERG products in detecting annual rainfall, with values very close to ideal throughout the region. The performance of IMERG products in monthly rainfall estimates was also quite homogeneous. Both monthly and annual POD, FAR, and CSI indices revealed a scaling factor that does not alter the ability to detect rainfall events.

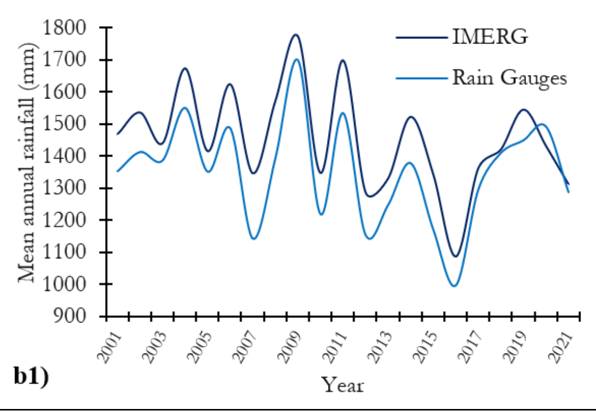
[40] conducted a study to validate IMERG rainfall estimates in Africa and found spatial patterns of CC, POD, FAR, FBS, and CSI that showed strong consistency between IMERG and TMPA (Multi-satellite Precipitation Analysis) over the Congo River basin in South Sudan. These authors concluded that the IMERG product can offer significant contributions to the understanding of climate processes in Africa and positive implications for the water, agriculture, and health sectors. [41]in evaluating the capability of GPM-era satellite products (IMERG and GSMaP (Global Satellite Mapping of Precipitation)), found that IMERG performed better than GSMaP, with high POD and CSI values for heavy rainfall. The authors suggest that IMERG can be a good alternative rainfall estimation product for regions with data gaps.

During the period of lower rainfall in the region, when there was a substantial decrease in peak rainfall (from May to September), it was observed that the IMERG product, compared to monthly rain gauge data, showed better agreement, significantly reducing overestimations. Under these circumstances, the metrics and graphs showed rainfall capture with similar patterns and with slight underestimation (see Figures 4 a1 and a2). In Figures 4 b1 and b2, it can be observed that the mean annual rainfall was overestimated compared to that of rain gauges, but with a correlation coefficient above 0.7.

Thus, IMERG had higher accuracies during the period of lower precipitation for the region (from May to September), also according to the metrics RMSE, MAE, and MBE, overestimating the precipitation by about 12%. According to[42]in a comprehensive evaluation of GPM in Canada, IMERG provided more reliable precipitation estimates during warmer months, especially in the summer, according to correlation coefficients and categorical indices. According to the authors, positive values of the hit bias indicated that IMERG overestimates the observed precipitation amount by ~10% on average, which was consistent with the results of other metrics, such as Rbias, MAE, and RMSE.

[43], in their evaluation of the satellite precipitation products IMERG in the Great Lakes region of Canada, observed that the 6-hour precipitation amount of IMERG showed better approximation in the warmer season, with a consistently overestimated frequency bias index. [44], in evaluations in southern Canada, compared the seasonality of IMERG in different regions and observed that the quality of IMERG is lower during the months of December to February, and performs better in the months of June to September.





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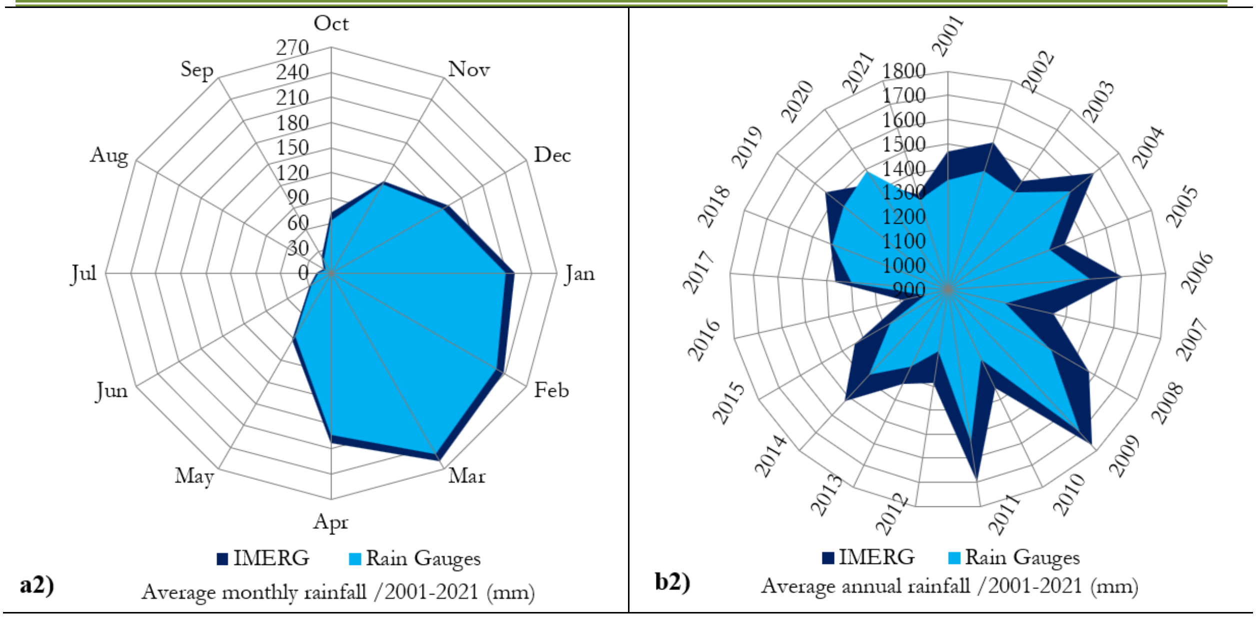

Fig. 3 Comparison between monthly data (a1 and a2) and annual data (b1 and b2) of rainfall between the rain gauges and the satellite values (IMERG).

In Figure4, observations of monthly and annual mean rainfall, frequency ratio, and mean error between the two rainfall assessment methods are indicated. The mean rainfall of IMERG is higher than that of rain gauges, and the characteristics of the mean rainfall range are consistent. The frequency ratio shows different characteristics between the two methods, and it can be observed that the IMERG product overestimates the precipitation.

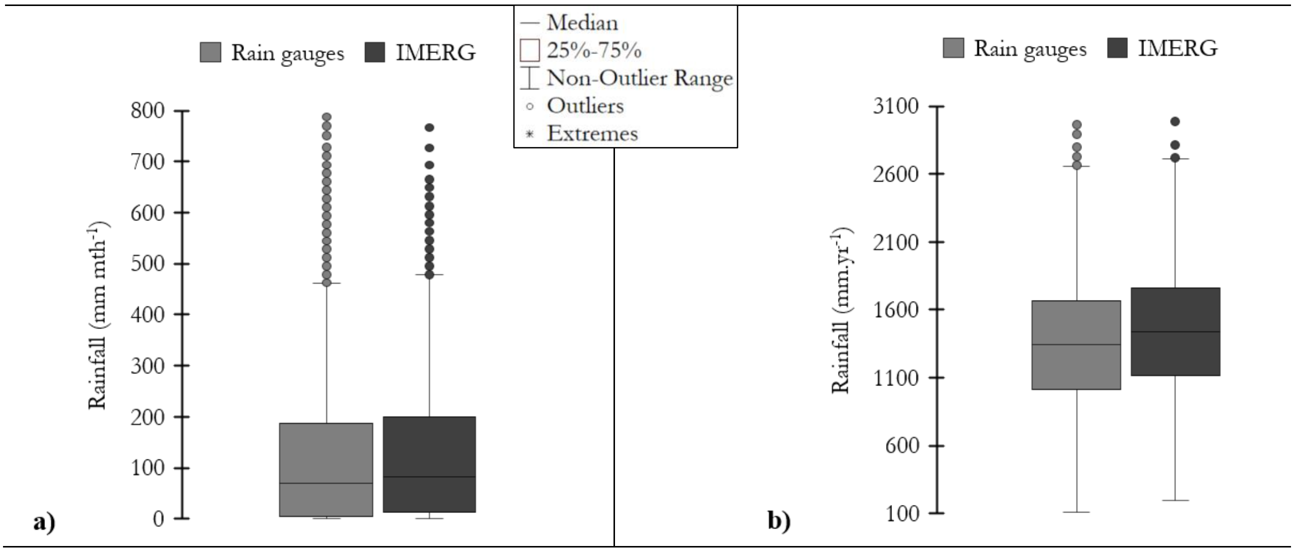

Fig. 4 Boxplot of precipitation frequency for the period 2001-2021 - a) monthly and b) annual

Figure 5 presents a simple visual comparison of observations and satellite estimates. Thus, it is possible to observe the monthly spatial distribution of precipitation from the 197 stations during the study period (October 2000 to September 2021).

It was possible to observe that IMERG successfully obtained the spatial structure of precipitation, as the magnitude and pattern are well reproduced, as shown by the metrics mentioned earlier. The highest occurrences of precipitation during the rainy season (from October to March) were between 20 and 434 mm. IMERG overestimated precipitation in March in the northwest region of the state of Tocantins, on the border with the states of Pará and Mato Grosso, which are outside of MATOPIBA, and also in the western part of the state of Maranhão. In a study of the performance of the precipitation data generated by the GPM (Global Precipitation

Measurement) and TRMM (Tropical Rainfall Measurement Mission) satellites over the eastern region of the state of São Paulo,[45]it was concluded that 68% of the measurements were overestimated and 32% were underestimated. In an evaluation of the latest IMERG products in the state of Paraná, [46], also found that IMERG data overestimated the high monthly precipitation values recorded by rain gauges, which occurred more frequently during the rainy season.

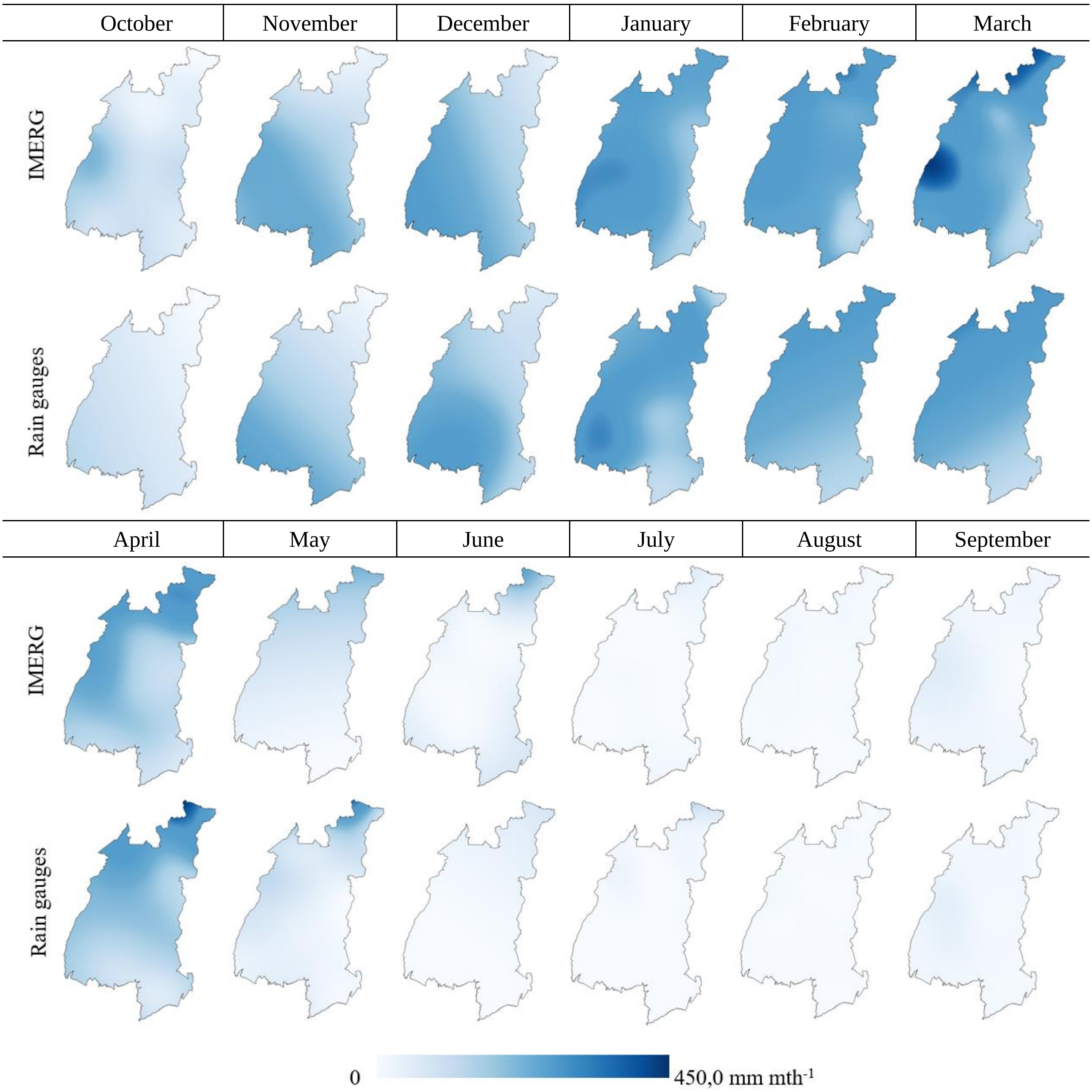

Fig. 5. Maps of monthly mean observed rainfall during the study period (October 2000 to September 2021) by rain gauges and the satellite product IMERG.

The spatial distribution of error metrics for estimating monthly and annual precipitation from IMERG is presented in Figure 6. The MBE and MAE values are spatially well distributed in the study area, with results close to the means. However, less precise metrics were observed throughout the study area, where IMERG shows greater discrepancies at some stations, due to the large area that the IMERG pixel covers, masking the variability of precipitation in areas with orographic effects.

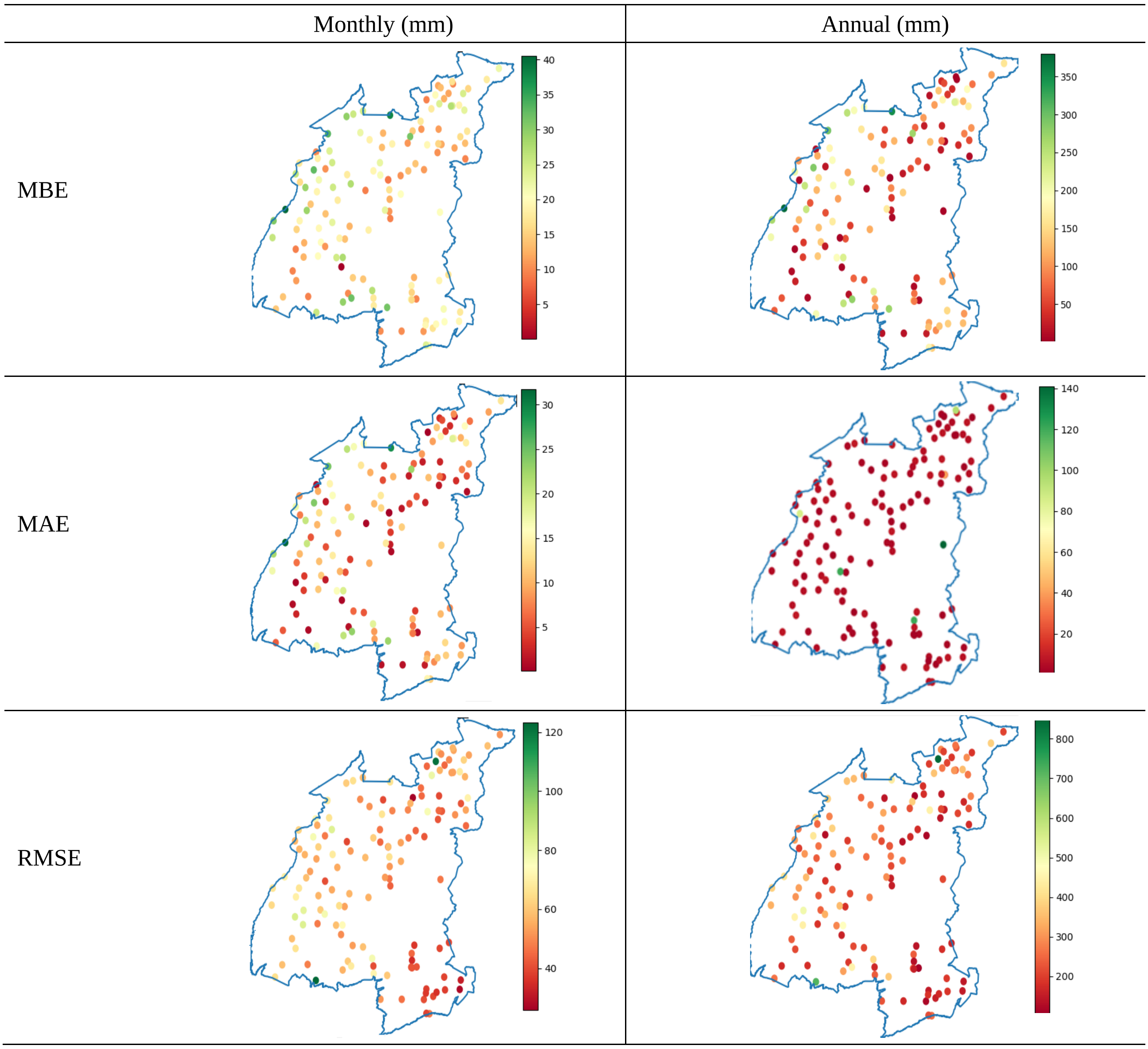

Fig. 6. Spatial distribution of error metrics on monthly and annual scales (October 2000 to September 2021)

[47] found that IMERG underestimated the total amount of rainfall by 50% at higher elevations and by 16% overall in a study that evaluated the GPM-IMERG satellite rainfall estimate and its dependence on microphysical rainfall regimes over the central southern Andes of Chile. According to the results of [48], in an evaluation of integrated multi-satellite retrievals for the Global Precipitation Measurement product in the São Francisco River basin (Brazil), IMERG was appropriate for representing rainfall over the basin. Performance varied depending on the location of the rainfall, with bias, ranging from -1.67 to 0.34 mm, RMSE ranging from 5.36 to 10.36 mm; IMERG and rain gauge correlation coefficients ranging from 0.28 to 0.61.

The metrics allowed us to evaluate the satellite product's ability to detect rainfall events. The IMERG detected rainfall over the MATOPIBA region, as reflected in Figure 7, for the entire study area, with a POD reaching values above 0.7, a relatively satisfactory CSI reaching values above 0.6, and a low Far-reaching value below 0.3. Regarding CC, the performance of IMERG exhibits values above 0.75, values close to the ideal (Table 2). [49] found that IMERG accurately detected rainfall in the Chocó Biogeographic Region in north western South America, with high POD and CSI and a low FAR. It is noteworthy that both scales have satisfactory POD and CSI and lower FAR, thus confirming the positive effects of the algorithm in detecting rainfall events. If we compare CSI and POD, the IMERG's ability to capture the probability of detecting rainfall is very good, with both having values close to 1.

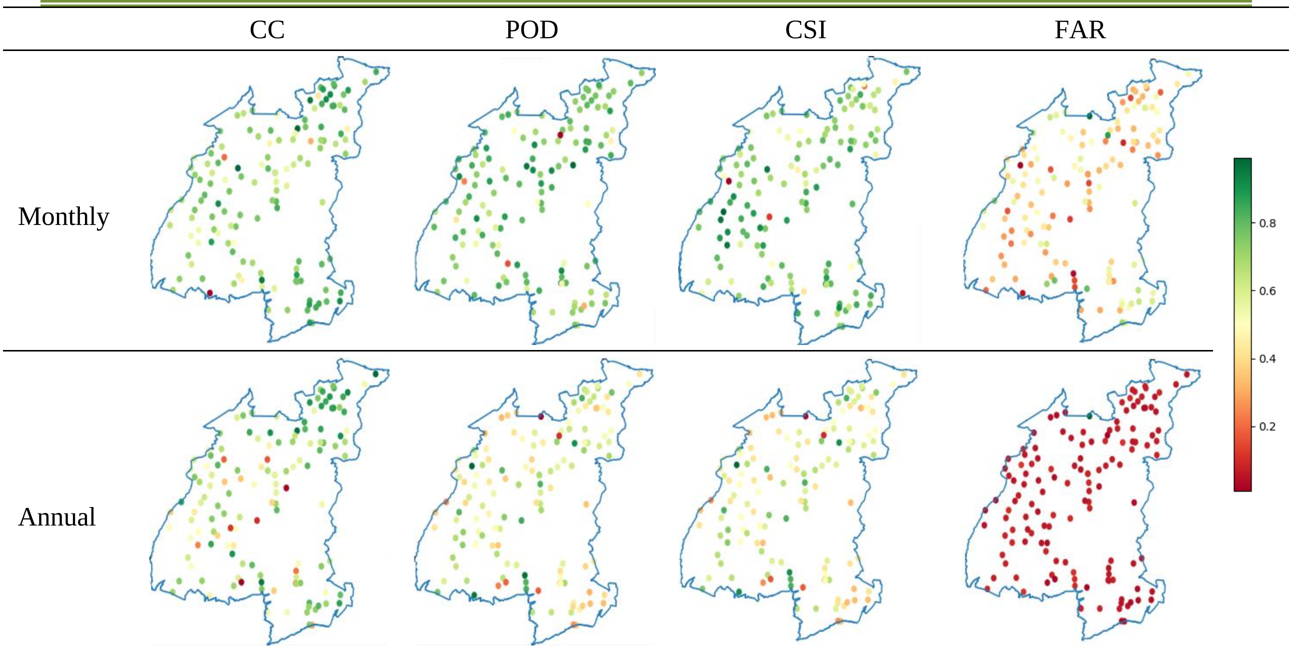

Fig. 7 - Spatial distribution of qualitative metrics of IMERG performance at monthly and annual scales.

In terms of the annual average, the rainfall distribution was similar between the two methodologies; however, there was an overestimation of maximum rainfall.[50]observed that on the northeast coast of Brazil, the IMERG presented errors and underestimated daily precipitation. This occurred, according to the study, because the region is characterized by warm rainfall events, as GPM sensors did not detect the process of orographically forced warm rainfall. Additionally, there may have been some influence from the sparse gauge density in the region. According to the same authors, in the Central Plateau region of Brazil, the IMERG reproduced annual and monthly rainfall with greater accuracy.

The annual mean rainfall for the MATOPIBA region estimated by the IMERG product between hydrological years (October 2000 to September 2021) was 2225.1 mm, while the mean rainfall from rain gauge data for the same period was 1965.8 mm, which means that, for the annual period, satellite data overestimated precipitation by about 13.2% (259.3 mm) compared to rain gauge data. This difference can be observed in Figure 8, in the central region of the area and in southern Maranhão on the border with the states of Tocantins, Bahia, and Piauí.

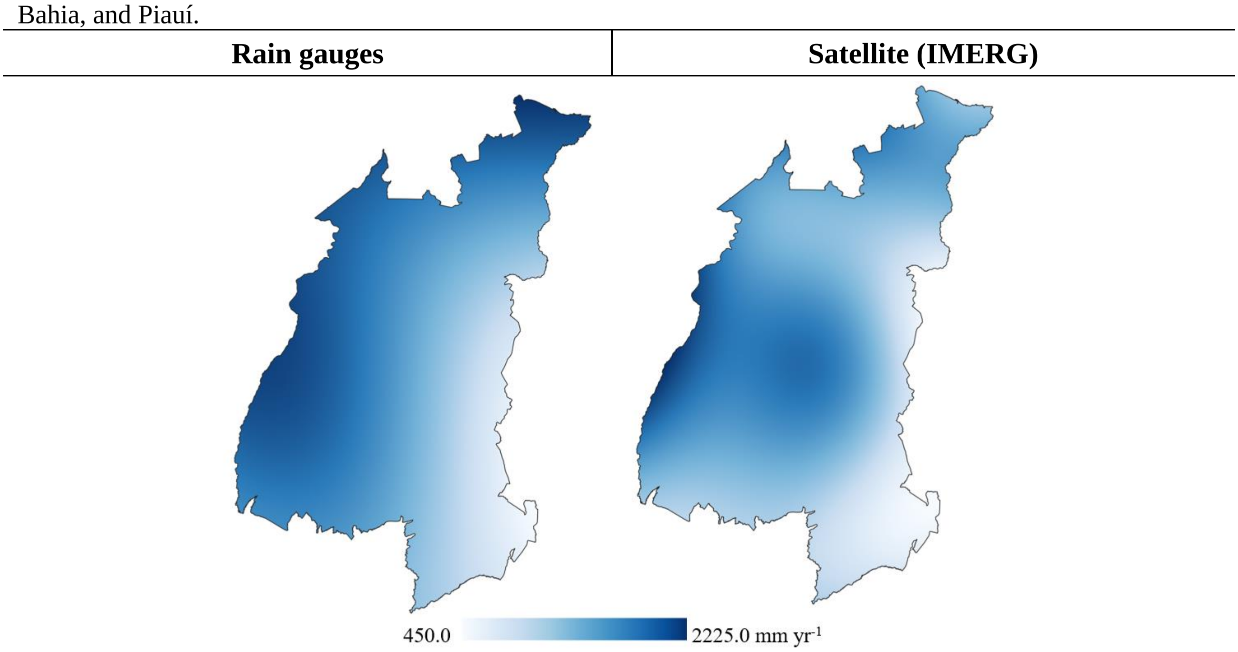

Fig. 8 - Map of annual mean rainfall observed during the study period (2001-2021) by rain gauges and IMERG

[51] identified that the GPM-IMERG products tend to overestimate the amount of rainfall above 300 mm per month over the Sio-Malabo-Malakisi River basin in East Africa. [52], in the evaluation and calibration of the reduced-scale rainfall of IMERG (sub-daily), in the Shanghai metropolitan region in China, concluded that IMERG performed better at the monthly time scale, followed by the annual scale (CC = 0.89 and 0.82, respectively). According to these authors, for annual rainfall, the relationship between IMERG and the rainfall from the rain gauge was less correlated than at the monthly scale. In addition, the mean annual rainfall of IMERG and rain gauges was 1510.0 and 1210.0 mm, respectively, indicating an overestimation of 24% by IMERG on average.

IV. CONCLUSION

This study evaluated the latest satellite precipitation estimates IMERG, comparing them with ground observations throughout the MATOPIBA region. Performance metrics were used to assess the product's performance on monthly and annual time scales over the period of 2001-2021. The IMERG identified the region's precipitation climatology with high accuracy, pointing out the areas with the highest rainfall.

The IMERG represented terrestrial rainfall quantities across all areas with a lower root mean square error (RMSE) and mean absolute error (MAE). In addition, higher values of the probability of detection (POD) and lower values of the false alarm ratio (FAR) indicated that rainfall occurrence was well distributed in the study region. Based on monthly evaluations, the IMERG provided more reliable rainfall estimates, with correlation coefficients above 0.81, when compared to annual evaluations.

Both on a monthly and annual scale, the IMERG overestimated rainfall by about 13%, especially during the wet season of the year. Nevertheless, it is considered that overall, the IMERG was able to represent the rainfall estimates of the region. Based on performance indices, it is suggested that IMERG algorithm data can be used as a reliable alternative to rain gauges in flood forecasting, as well as in drought monitoring and agricultural planning studies in this region, as the number of rain gauges with continuous data is quite limited

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