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EVALUATION OF TRMM 3B43V7 SATELLITE PRECIPITATION IN THE PANTANAL OF MATO GROSSO DO SUL IN THE YEARS 1998 TO 2019

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Abstract

Remote sensing can assist in the acquisition of scarce surface data. The analyzes for validation of the precipitation product estimated by the TRMM satellite (Tropical Rainfall Measuring Mission) were carried out with the precipitation data observed on the surface during the period from 1998 to 2019. For this purpose, precipitation data from the Pantanal biome meteorological stations were used, located between the 16 and 22°S parallels and the 55 and 58°W meridians, and compared with the data from the TRMM 3B42 V7 product algorithms. Statistical analysis was performed based on the correlation coefficient, root mean square error (RMSE), and relative bias (BIAS) between the monthly precipitation data observed on the surface and the estimated precipitation data. The results found for product 3B43 V7 indicated that the precipitation estimates were representative when compared to the surface observations. However, when compared for the rainy and dry periods, there was underestimation and overestimation, respectively, of the product. The product 3B42 V7 satisfactorily represents the precipitation that occurs on the surface.

Keywords: Tropical Rainfall, Remote Sensing, Conventional Meteorological Observation Precipitation Estimate.

Resumo / Resumen

AVALIAÇÃO DA PRECIPITAÇÃO DO SATÉLITE TRMM 3B43V7 NO PANTANAL DE MATO GROSSO DO SUL NOS ANOS DE 1998 A 2019

O sensoriamento remoto pode auxiliar na aquisição de dados de superfície escassos. As análises para validação do produto de precipitação estimado pelo satélite TRMM (Tropical Rainfall Measuring Mission) foram realizadas com os dados de precipitação observados na superfície durante o período de 1998 a 2019. Para tanto, foram utilizados dados de precipitação de estações meteorológicas do bioma Pantanal, usados, localizados entre os paralelos de 16 e 22°S e os meridianos de 55 e 58°W e comparados com os dados dos algoritmos de produto TRMM 3B42 V7. A análise estatística foi realizada com base no coeficiente de correlação, erro quadrático médio (RMSE), e viés relativo (BIAS) entre os dados de precipitação mensal observados na superfície e os dados de precipitação estimados. Os resultados encontrados para o produto 3B43 V7 indicaram que as estimativas de precipitação foram representativas quando comparadas às observações de superfície. Porém, quando comparadas para os períodos chuvoso e seco, houve subestimação e superestimação, respectivamente, do produto. O produto 3B42 V7 representa de forma satisfatória a precipitação que ocorre na superfície.

Palavras-chave: Chuva Tropical, Sensoriamento Remoto, Estimativa de Precipitação por Observação Meteorológica Convencional.

EVALUACIÓN DE LA PRECIPITACIÓN DEL SATÉLITE TRMM 3B43V7 EN EL PANTANAL DE MATO GROSSO DO SUL EN LOS AÑOS 1998 A 2019

La teledetección puede ayudar en la adquisición de datos de superficie escasos. Los análisis para la validación del producto de precipitación estimado por el satélite TRMM (Tropical Rainfall Measuring Mission) se llevaron a cabo con los datos de precipitación observados en superficie durante el período de 1998 a 2019. Para ello, se utilizaron los datos de precipitación de estaciones meteorológicas em el bioma de Pantanal, utilizados, ubicados entre los paralelos 16 y 22°S y los meridianos 55 y 58°W y comparados con los datos de los algoritmos del producto TRMM 3B42 V7. El análisis estadístico se realizó con base en el coeficiente de correlación, el error cuadrático medio (RMSE), y el sesgo relativo (BIAS) entre los datos de precipitación mensual observados en la superficie y los datos de precipitación estimados. Los resultados encontrados para el producto 3B43 V7 indicaron que las estimaciones de precipitación fueron representativas en comparación con las observaciones de superficie. Sin embargo, cuando se compararon para los períodos lluvioso y seco, hubo subestimación y sobreestimación, respectivamente, del producto. El producto 3B42 V7 representa satisfactoriamente la precipitación que se produce en la superficie.

Palabras-clave: Lluvia Tropical, Teledetección, Estimación de Precipitación de Observación Meteorológica Convencional.

INTRODUCTION

The primary source of water for human activities in most of the world is rainfall. Precise knowledge of the amount, frequency, and intensities of rainfall at a given location is crucial for planning its full utilization, as rainfall data play an important role in the design and management of water and environmental systems (Abreu et al., 2022). The values of rainfall vary from place to place, day to day, month to month, season to season, and also year to year. So, the analysis of the amount, intensity, and distribution of rainfall data for a certain period is essential for hydrologists, meteorologists decision-makers.

Recent studies have documented that the rainfall data with spatial and temporal resolutions are essential for hydrological research, water resource management, agricultural production, early drought and flood alerts, and for monitoring purposes (Dubreuil et al., 2004; Collischonn et al., 2007; Chen et al., 2013b; Habib et al., 2012; Seyyedi et al., 2015; Tang et al., 2015; Chen & Li, 2016; Zhao et al., 2018).

Long-term records of daily rainfall have been recorded for years, so this information for locations in the world are generally available and can be utilized for analysis. In the past, the spatial distribution of rainfall, climate zones, floods and droughts were analyzed using these data. Although we have a large amount of data, not everything that should be known about precipitation is yet known. A long-term change in climate variables such as precipitation and temperature affect the ecosystems and for this reason, climate models are constantly being updated.

The importance of precise knowledge on the subject of rainfall also requires the constant improvement of their measurement methods. Although there are many methods, it is still difficult to make accurate estimates using any of them. Thus, measuring the amount of precipitation reaching the ground is not as simple as it might seem. Precipitation data are traditionally acquired from rain gauges or more reliable weather radars, but rain gauges are generally scarce and unevenly distributed due to limited access to certain areas such as e.g. deserts, mountains, and oceans (Xie and Arkin, 1996; Maggioni, Meyers & Robinson, 2016; Zhu et al., 2017). The low density of weather station distributions reduces the reliability of the information because only complete and long series increase the quality of analysis.

Today, scientists can measure and estimate precipitation also indirectly using remote sensing techniques (e.g. from radar systems and Earth-observing satellites). However, radars suffer from limited spatial coverage, especially in oceanic regions, and many researchers are looking for alternatives to overcome these limitations (Kidd et al., 2012; Liu, 2015; Ma et al., 2016). The data from satellite sensors when compared to data from the rain gauge, in addition to having a greater range in regions of difficult access, also produce data with a more refined temporal and spatial resolution (Shrivastava et al., 2014; Mantas et al., 2015).

The Tropical Rainfall Measurement Mission (TRMM) was developed by the National Aeronautics and Space Administration (NASA) and the Japanese Aerospace Exploration Agency (JAXA) in 1997 and provides information on precipitation over tropical and subtropical regions (Kummerow et al., 1998; Kummerow et al., 2001; Huffman et al., 2007; Mehta & Yang, 2008; Yang & Smith, 2008). Measurements from TRMM deepened knowledge of tropical rainfall and provided three-dimensional images of storm intensity and structure from space using the first satellite-borne weather radar. Satellite precipitation estimates have been a focus of attention due to their temporal and spatial variability (Chen et al., 2013a; Chen & Li, 2016; Guo et al., 2016), but satellite products recorded deviations and errors caused by uncertainty in the sampling frequency algorithms (Nair, Srinivasan & Nemani, 2010). Satellite products must be checked and adjusted by conventional rain gauge data before being applied. The performance of the TRMM 3B43V7 product varies due to different altitudes and geographic locations (Tan et al. (2018) in Singapore; Karaseva, Prakash & Gairola (2012) in Kyrgyzstan; Zhu et al. (2017) in southwest China; Tan et al. (2017) in Malaysia; Darand, Amanollahi and Zandkarimi (2017) in Iran; Wang et al. (2017) in the Qinling-Daba mountains; Jin, Zhang and Huang (2015) in Yangtze; Tao et al. (2016) in Jiangsu province in China and Chen & Li (2016) in China).

Also in Brazil, several studies have been carried out to validate precipitation data for different regions and demonstrating that there is a good relationship between precipitation estimates and TRMM satellite data, including Silva-Fuzzo & Rocha (2016), Camparotto et al. (2013), Almeida et al. (2015), Pessi et al. (2019).

In the Pantanal of Mato Grosso do Sul, the monitoring of the precipitation is limited by scarcity and uneven distribution of weather stations due to difficult access regions. The precipitation measurements obtained from sparsely spaced rain gauges are not representative, and are therefore not always adequate for research, especially for large areas such as the Pantanal. Therefore, the satellite is considered important option for acquiring rainfall estimates in the absence of ground-based measurements in this area. This was the main motivation for the present study. An evaluation of the TRMM 3B43V7 product in the Pantanal of Mato Grosso do Sul is urgent because will provide theoretical support for the application of TRMM 3B43 in monitoring and alerting droughts in the Pantanal. This work evaluated the accuracy and reliability of the TRMM 3B43V7 product by comparing its precipitation estimates with observations of the ground-based meteorological stations in the Pantanal from January 1998 to December 2019. This study might benefit the improvement of precipitation monitoring and forecasting by using satellite precipitation products in this area.

MATERIALS AND METHODS

STUDY AREA

The study was carried out in the Brazilian part of the Pantanal (latitude 16 - 22°S, longitude 55 - 58°W). The Pantanal is the largest wetland in the world, covering an area of over 160,000 square kilometers, located in the center of South America (SA), and sprawls across three countries - Bolivia, Brazil, and Paraguay. At 140,000 square kilometers, Pantanal occupies an area in the Central-West region of Brazil, according to the IBGE Geographic Dictionary (IBGE), of which around 63% is located in the state of Mato Grosso do Sul and 37% in the state of Mato Grosso. The average altitude is 110 m, a slope ranging from 6 to 12 cm per kilometer in the east-west direction and from 1 to 2 cm per kilometer in the direction region north-south (NS) - (Figure 1).

In the state of Mato Grosso do Sul, the following municipalities belong to the Pantanal of Mato Grosso do Sul: Anastácio, Aquidauana, Bodoquena, Corumbá, Coxim, Miranda, and Porto Murtinho. The main rivers that descend from the plateau to the plains are from north to south, Paraguay, Bento Gomes, Cuiabá, São Lourenço - Itiquira, Taquari, Negro, Aquidauana - Miranda, Nabileque, and Apa.

THE CLIMATE IN THE PANTANAL

According to Köppen's classification, most of the territory is in the tropical climate zone (Alvares et al., 2013). The following climate types occur in the Pantanal: the Aw type (tropical with a dry season in winter) with two well-defined seasons: i) dry (May to September) and ii) rainy (October to April) (Teodoro et al., 2015) appears in the south of the state of Mato Grosso (region of the Pantanal), with annual precipitation of 1,400 mm. The Am climate type (subtropical humid and subhumid) appears in the west of the Mato Grosso do Sul, in the lower Pantanal, where annual rainfall varies between 1,300 and 1,600 mm, and also in the central region of the state, where rainfall is slightly higher and reaching 1,900 mm per year. The Af climate type (tropical humid or super humid) appears in the southwest of Mato Grosso do Sul, in the south of the Pantanal, in southernmost locations, and always at altitudes below 400 m, where annual precipitation varies between 1,400 and 1,800 mm. In a small place, in the highlands of the Pantanal, above 900 m altitude, the Cfa climate type (subtropical hot summer climate) is observed (Alvares et al., 2013).

The different climatic characteristics of the Pantanal are determined by the relief conditions and climatic interactions. In addition to this, the strong influence of neighboring biomes, such as the Cerrado, the Amazon, and the Bolivian and Paraguayan Chacos (Alho et al., 2019).

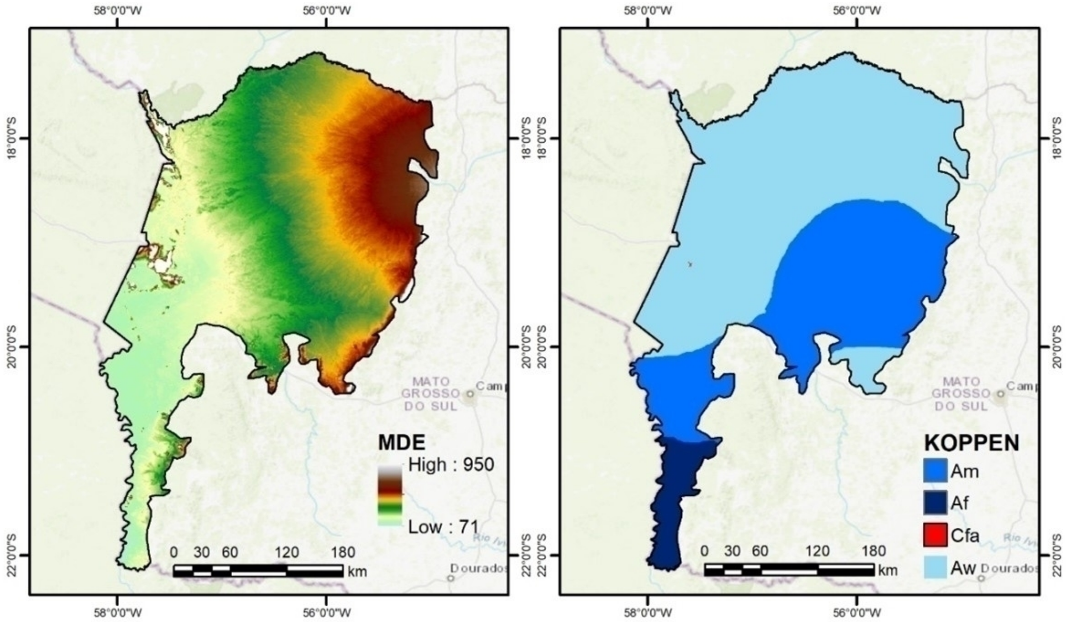

Figure 1 - Location and extent of the Pantanal in South America, with Köppen classification and digital elevation model - DEM (m), respectively.

Location	Latitude (°S)	Longitude (°W)	Altitude (m)	Period (years)
Anastácio	-19.6	-56.2	106	1998-2019
Aquidauana	-22.5	-55.8	147	1998-2019
Bodoquena	-19.9	-57.0	133	1998-2019
Corumba	-19.0	-57.6	118	1998-2019
Coxim	-18.5	-54.7	238	1998-2019
Miranda	-20.2	-56.4	125	1998-2019
Porto Murtinho	-21.7	-57.9	90	1998-2019
Rio Negro	-19.4	-55.0	233	1998-2019

Table 1 - Altitude (m), latitude and longitude (°) and observation period for the precipitation (mm) of eight locations in the state of Mato Grosso do Sul, Brazil.

TRMM SATELLITE DATA AND CONVENTIONAL WEATHER STATIONS (EMC)

HISTORICAL SERIES OF MONTHLY PRECIPITATION

The background information concerning data from the conventional meteorological stations and satellite observation used in this study is described in following section. The historical series of rainfall data at the 8 conventional meteorological stations across the Pantanal Sul-Mato Grosso - MS (Figure 1) were collected for the period from January 1998 to December 2019. The location and observation period are presented in Table 1. The data were obtained from the hydrometeorological database of the National Water Agency (ANA) - (ANA, 2020), available at the Hidroweb - Hydrological Information System (http://www.ana.gov.br/), and from the meteorological data bank of the National Institute of Meteorology (INMET). The data were provided as the accumulated daily rainfall in millimeters for each station.

Firstly, quality control of the data from each station was performed to identify if there were failures. The historical series with failures were eliminated and filled by climatological normal for each of 8 stations according to the performed by Teodoro et al. (2015). For the evaluated period, most of the data referring to the meteorological stations presented a maximum of 5% of data failures. Secondly, the average monthly rainfall for rain gauges for the period 1998-2019 was added up for each station, and month and finally, the average annual rainfall was added up for each station.

The data for the TRMM-3B43 product was obtained from the Giovanni website (NASA, 2019) available at the link: https://giovanni.gsfc.nasa.gov/giovanni/. The files are made available in ASCII format with a regular grid of points (grid-point). The collected data refer to the quadrants that cover the entire limit of the meteorological stations (Figure 1).

The observations from 8 conventional meteorological stations and satellite time series were compared using following a pixel-based approach. That is, precipitation estimates at each meteorological station were compared with satellite estimates at the corresponding grid's pixel. Comparisons were performed on a monthly and annual basis.

The accuracy of the satellite estimates can be evaluated using several statistical indices. In this study were chosen to compare the differences and correlations between satellite estimates and observations from conventional meteorological stations the relative bias (BIAS), correlation coefficient (r), and root mean square error (RMSE). These statistical indices were often used in validation studies (Yang & Luo, 2014, Liu et al., 2020, de Almeida et al., 2020).

The statistical indices can be calculated using the following equations:

$$BIAS = \frac{(\sum_{i=1}^{n} Rf_{TRMM-i} - \sum_{i=1}^{n} Rf_{obs-i})}{\sum_{i=1}^{n} Rf_{obs-i}}$$

$$r = \frac{\left(\sum_{i=1}^{n} Rf_{obs-i} - \overline{Rf_{obs}}\right) \cdot \left(\sum_{i=1}^{n} Rf_{TRMM-i} - \overline{Rf_{TRMM}}\right)}{\sqrt{\left(\sum_{i=1}^{n} Rf_{obs-i} - \overline{Rf_{obs}}\right)^2 \cdot \left(\sum_{i=1}^{n} Rf_{TRMM-i} - \overline{Rf_{TRMM}}\right)}}$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(Rf_{TRMM-i} - Rf_{obs-i})^2}{n}}$$

where Rfobs-i is the observed precipitation, RfTRMM-i is the precipitation value estimated by TRMM 3B43; Rfobs is the observed average precipitation and RfTRMM is the average precipitation estimated by the TRMM of 3B43; n is the number of observations.

The relative BIAS is the overall deviation of the TRMM 3B43V7 rainfall estimates from the meteorological stations data set, which indicates overestimation (BIAS > 10%) or underestimation of the satellite estimates (BIAS < -10%) and approximately equal satellite estimates and observations from the meteorological stations (BIAS range from -10% to 10%) (Yang and Luo, 2014).

The RMSE measures the mean error between observations from the meteorological stations and TRMM 3B43V7 rainfall estimates. The RMSE equal to 0 indicates no errors. The higher the RMSE, the higher the difference between the satellite rainfall estimates and observations from the meteorological stations.

The correlation coefficient measures the correlation between observations from the meteorological stations and TRMM 3B43V7 rainfall estimates, with the value ranges between -1 and 1. The value 0 indicates no correlation while a value close to 1 (or -1) indicates a high correlation.

RESULTS AND DISCUSSION

The rainfall regime in the Pantanal is regulated according to the performance of the dynamic systems of microscale, mesoscale and synoptic scale. In this case, the local convection contributes to the formation of summer clouds, due to the diurnal heating of the surface, resulting in large daily pluviometric volumes in the rainy season, which also contributes to the intensive space-time variability in the hydrological cycle in the Pantanal. Considering the accumulated monthly precipitation over the Pantanal, there is a defined seasonal cycle, with higher rates in the rainy period (October to April) and lower rates in the dry period (May to September).

In the period with the highest rainfall, there is the action of air masses, that is, there is an intensification and expansion of the Continental Air Mass over SA and oscillation to the south of the Intertropical Convergence Zone (ITCZ) and the action of Bolivian high (BH), responsible rain production in the Pantanal. In the drier quarter, the South Atlantic Subtropical High (SASH) occurs, at that time there is strong atmospheric subsidence, due to anticyclones formed over the continent, inhibiting the formation of rain clouds in the central region of Brazil, that is, the rainfall index is managed by frontal rains (Franca, 2015).

The average annual precipitation during the study period was approximately 1292 mm for the conventional meteorological stations and ranged from 307 mm in the dry season (April to September) to 927 mm in the rainy season (October to March), showing that the highest rainfall is observed in the plateau. The average annual precipitation was approximately 1322 mm for the TRMM and ranges from 326.9 mm in the dry season to 936 mm in the rainy season.

Figure 2 shows the variation of the monthly average precipitations of satellite data (TRMM) and the monthly average precipitations of data from conventional meteorological stations for the period from 1998 to 2019. The average monthly precipitation from conventional stations was observed at 103.2 mm, ranging from 0 to 333.36 mm, with a standard deviation of 73.26 mm, skewness of 0.54, and median of 99.91 mm. The average precipitation from TRMM satellite data was observed at 105.61 mm, range from 0.13 to 336.08 mm with a standard deviation of 72.02 mm, skewness of 0.55, and median of 101.48 mm.

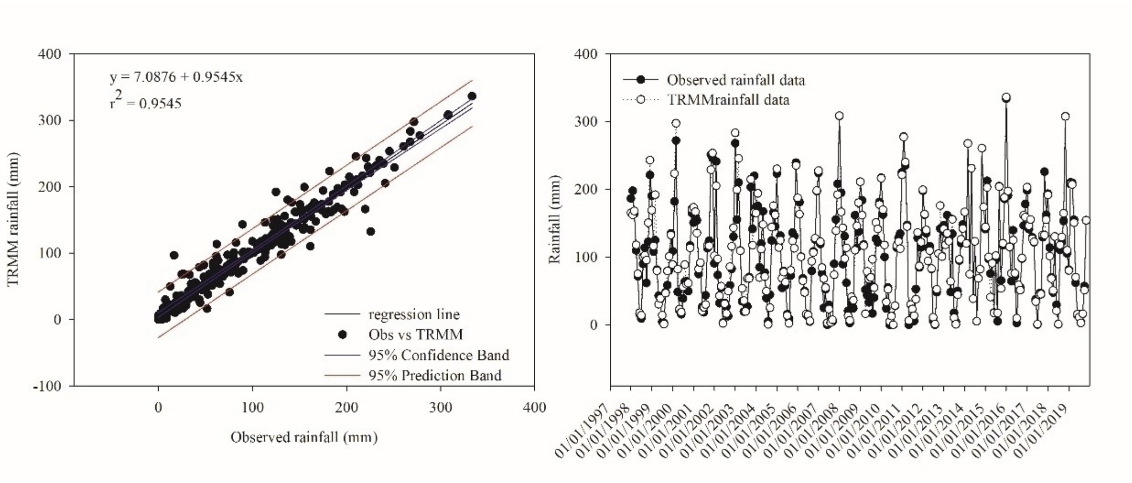

Figure 2 - Results of the monthly averages of the temporal distributions of the precipitations during the study period from 1998 to 2019 and analysis of correction for both data sources (TRMM-3B43 and conventional stations) of the eight locations evaluated in the wetland.

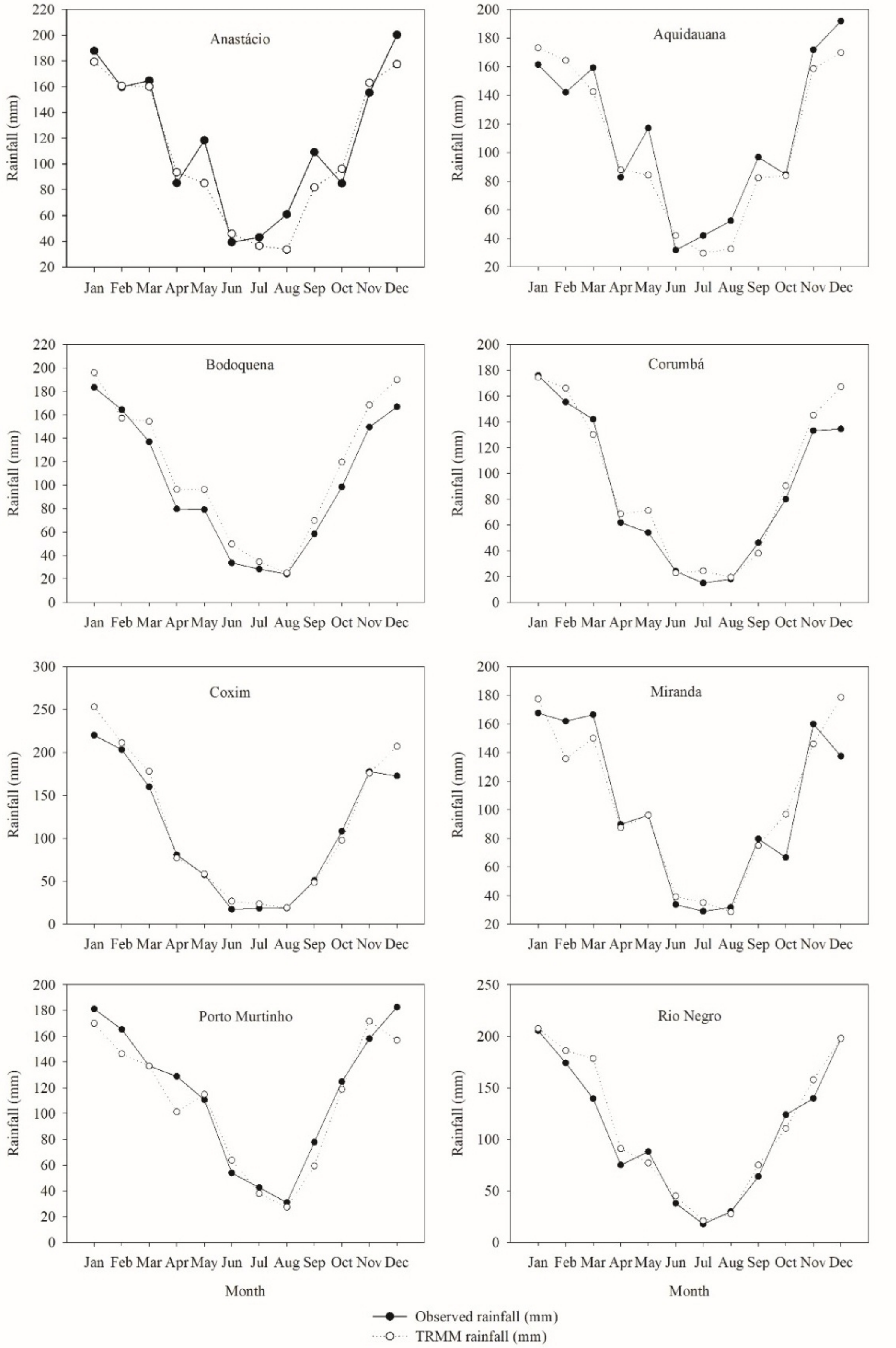

Figure 3 - Comparison of the monthly average precipitation data (mm) of the conventional meteorological stations (CMS) between the years 1998 to 2019 for the eight locations in the Pantanal of Mato Grosso do Sul.

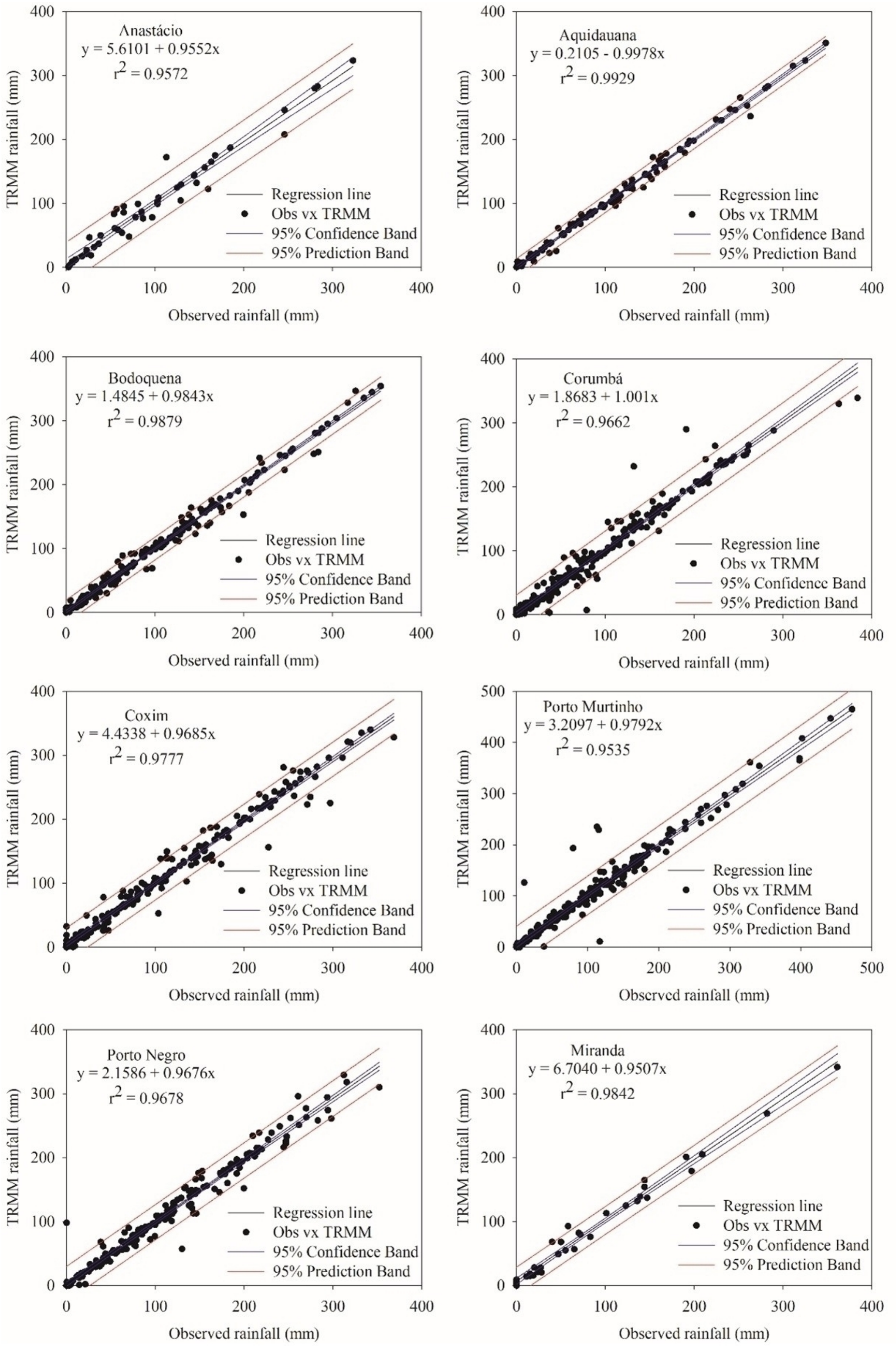

Figure 4 - Analysis of correlations of the monthly average rainfall data (mm) from the conventional meteorological stations (CMS) and from the TRMM satellite product 3B43 between the years 1998 to 2019 for the eight locations in the Pantanal of Mato Grosso do Sul.

It is possible to observe that there is a similarity, to a large extent, between the TRMM and EC precipitations (Figure 3). Almazroui (2011) and Pessi et al. (2019) also observed a similarity, for monthly data in the period 1998 to 2009, between evaluations of the TRMM satellite and stations in Saudi Arabia and Mato Grosso.

Figures 2 and 4 show the results of the statistical analyzes carried out between the monthly rainfall data. The data estimated by the TRMM product 3B43 and observed in the conventional meteorological stations showed a high correlation in all evaluated conventional meteorological stations, with an average correlation coefficient of 0.94, significant at 5% probability, when considering the data from all locations together (Figure 2).

It was found that the highest values of BIAS occurred in the month of June (Table 2) as also observed by Camparotto et al. (2013). The highest BIAS value was 0.48 for the Bodoquena station in June and the highest RMSE value was 1688.30 for the Miranda station in December. This characteristic can be explained due to the convective rains, which are generally strong and occur in a punctual manner (Camparotto et al., 2013).

Statistics	Anastácio	Aquidauana	Bodoquena	Corumbá	Coxim	Miranda	Porto Murtinho	Rio Negro
				Average				
r	0.9591	0.9548	0.9893	0.9806	0.9899	0.9405	0.9685	0.9790
BIAS	-0.8747	-0.7936	1.9964	1.3607	1.1679	0.6504	-0.7389	0.9401
RMSE	17.2675	17.1717	15.4520	13.2117	15.6312	18.1474	14.7755	15.0652
				Monthly BIAS				
Month	Anastácio	Aquidauana	Bodoquena	Corumbá	Coxim	Miranda	Porto Murtinho	Rio Negro
Jan	-0.0456	0.0731	0.0691	-0.0089	0.1508	0.0587	-0.0623	0.0104
Feb	0.0055	0.1558	-0.0440	0.0691	0.0399	-0.1620	-0.1148	0.0686
Mar	-0.0282	-0.1051	0.1272	-0.0846	0.1133	-0.0999	0.0003	0.2786
Apr	0.0988	0.0623	0.2102	0.1085	-0.0488	-0.0258	-0.2142	0.2116
May	-0.2823	-0.2812	0.2168	0.3204	0.0146	0.0010	0.0375	-0.1243
Jun	0.1661	0.3241	0.4801	-0.0502	0.5570	0.1631	0.1840	0.1921
Jul	-0.1566	-0.2954	0.2196	0.6407	0.2867	0.2044	-0.1091	0.1825
Aug	-0.4507	-0.3752	0.0394	0.0768	0.0109	-0.0961	-0.1195	-0.0757
Sep	-0.2504	-0.1501	0.1974	-0.1758	-0.0489	-0.0580	-0.2369	0.1749
Oct	0.1330	-0.0092	0.2160	0.1310	-0.0972	0.4526	-0.0481	-0.1075
Nov	0.0498	-0.0772	0.1262	0.0901	-0.0097	-0.0868	0.0854	0.1294
Dec	-0.1140	-0.1155	0.1385	0.2437	0.1992	0.2992	-0.1412	-0.0007
				Monthly RMSE				
Month	Anastácio	Aquidauana	Bodoquena	Corumbá	Coxim	Miranda	Porto Murtinho	Rio Negro
Jan	73.3427	138.9350	160.6722	2.4460	1100.0078	96.6507	127.3196	4.5896
Feb	0.7719	489.8375	52.3960	115.1931	65.7058	687.2262	359.3947	142.6051
Mar	21.5952	279.8980	303.5206	144.3922	328.0050	276.6012	0.0012	1509.8627
Apr	70.6107	26.4450	280.4669	45.0364	15.5702	5.3310	760.8212	251.6821
May	1116.0772	1083.2676	294.2032	299.1228	0.7133	0.0101	17.2105	119.4117
Jun	42.4942	105.6510	259.3590	1.4556	93.0260	30.2558	98.0290	52.6017
Jul	45.5890	153.3469	38.5771	90.6873	27.8832	35.3840	21.5034	10.2892
Aug	753.1007	383.9174	0.8995	1.8960	0.0428	9.2859	13.6866	5.0757
Sep	746.2538	210.5079	132.6120	65.9344	6.1933	21.3316	338.6028	124.5778
Oct	127.3682	0.6025	451.6697	109.8209	110.4314	909.2637	35.9564	176.5516
Nov	59.6408	175.6508	356.6072	143.9891	2.9475	192.2860	182.1232	326.2534
Dec	521.1552	490.3272	534.1810	1074.6074	1181.4859	1688.2968	665.1308	0.0169

Table 2 - Annual and monthly averages of r, Bias and RMSE for the eight cities located in the Pantanal in Mato Grosso do Sul, between 1998-2019.

Pereira et al. (2013) obtained an error of up to 53 mm in the comparison between the data estimated by the TRMM and the values observed in surface stations in the Midwest regions and Camparotto et al. (2013) obtained values equal to 81.6 mm also for the month of January (Aires et al., 2016).

In the winter months, the values of BIAS were lower, with the average of 0.083 being the lowest value observed in the month of August with (-0.45) mm for the city of Anastácio (Table 2). In this season of the year, rainfall is of low intensity, often caused by the entry of cold air masses, which cover a large region of the State of Mato Grosso do Sul.

According to Almeida et al. (2015), when variations in seasonal precipitation trends occur, this anomaly is mainly due to the satellite overestimating or underestimating the values in relation to the observed data from EMC's.

Other studies have also reported these differences (Collischonn et al., 2007; Nóbrega et al., 2008; Rozante et al., 2010; Almeida et al., 2015; Silva-Fuzzo and Rocha, 2016) and explain that there is a trend of TRMM in overestimating precipitation over the continent, as well as report the TRMM's ability to estimate dry and rainy periods. According to the authors, this factor has not yet been fully explained and may be related to some processing error, both in the reading of rain gauges and in the generation of satellite estimates.

Rozante et al. (2010) analyzed and showed that product 3B42 tends to overestimate the precipitation by around 7% and this fact is associated with the product's deficiency in estimating hot clouds over the region. It was also found that it is possible to have an apparent relationship between latitude, showing that this trend increases along with latitude (Viana et al., 2010).

In this sense, the differences between the data derived from the TRMM satellite and obtained by the meteorological stations (EC) may be a consequence of the differences in scale between them, since the rain gauge is a point estimate, while the satellite represents an average estimate in the pixel (Almeida et al., 2015).

Considering hydrographic basins, Collischonn et al. (2007) evaluated that the precipitation estimates provided by the TRMM are consistent and reproduce the rainfall regime fairly accurately, confirming that the precipitation data estimated from the satellite can be an efficient and inexpensive alternative when compared to soil instruments, such as pluviometric stations.

For Nóbrega et al. (2008), TRMM can analyze seasonal variability, satisfactorily representing dry and rainy periods. Still, according to the authors, the TRMM data correlates satisfactorily with the densest network of rain gauges. Likewise, the analyzes for the 3B43 algorithm showed a high degree of reliability in the studied areas (Oliveira and Angelis, 2010; Viana, 2010; Fleming et al., 2011), including in relation to the presence of convective clouds over deforested regions.

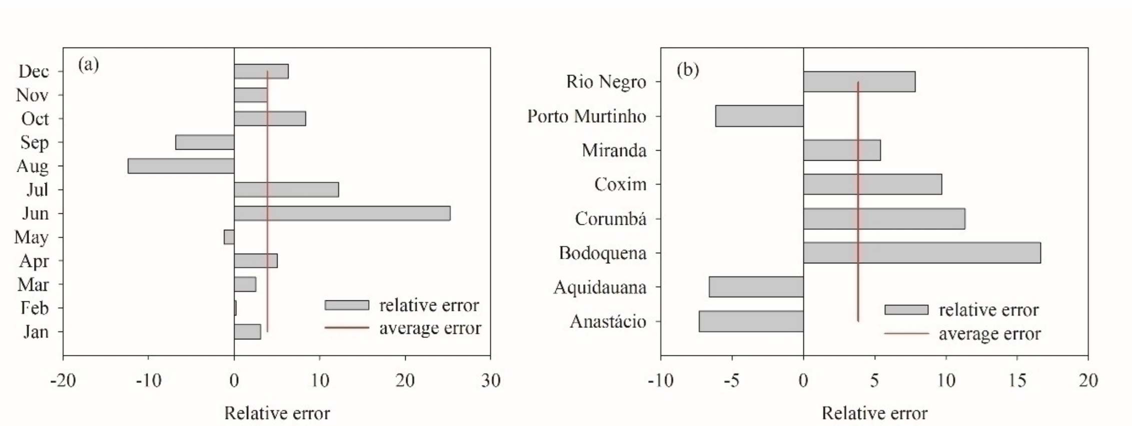

Figure 5 - Average of the relative error of the meteorological stations in the function of the months (a) and relative errors of the historical series of the meteorological stations (b).

The relative error of presented values is considered adequate, according to Van Liew et al. (2007), who considered the performance of the hydrological simulation to be satisfactory for error values below 25%.

The relative error showed that the satellite tends to underestimate/overestimate the monthly average precipitation, as the values found were negative/positive, so the satellite tends to overestimate the monthly average precipitation data by 3.8% for the 22 years of analysis for the annual period. However, in the dry period, the overestimation of the satellite was higher by 25.2%. These results corroborate with Collischonn et al. (2007), who found an 8% positive bias in the Paraguay basin in the state of Mato Grosso, and Viana et al. (2008) who found a positive bias of around 7% in the southern region of Brazil, in which they state that the product 3B42 tends to overestimate precipitation (Figures

5a and b). The biggest relative error was for the city of Bodoquena with 16.6% (Figure 5b).

The results of the monthly correlations for each region indicate that the data estimated by the TRMM show a good agreement (on average 90%) with the data from the networks of meteorological stations. Still, the monthly analyzes indicate that the RMSE, frequently used to verify the differences between the estimated and observed data, has average values between 15.8 mm. In addition, TRMM data show an average tendency to overestimate monthly rainfall by 3.8%. However, precipitation estimates show seasonal variation very similar to that presented by the data observed in meteorological stations, for each study region.

However, the analysis by period showed that the 3B43 TRMM tends to underestimate the precipitation in the rainy period (November to April), while in the dry period (May to October) the estimated precipitation values are higher than the precipitation observed by the rain gauge. These results are similar to those found by Collischonn et al. (2008) when analyzing the Tapajós river basin between 1998 and 2006, however, claim that for precise conclusions about why such satellite behavior is needed, more specific studies are needed.

Possible factors may be related to the fact that the TRMM product considerably overestimates dry season precipitation. The lower precipitation values in this period associated with increased fires and, consequently, increased aerosol emissions to atmospheres may be the cause of the overestimation of precipitation (Souza et al., 2020).

The largest source of aerosols to the atmosphere in SA are emissions from forest fires and savannahs, which occur mainly in the dry season (Souza et al., 2020) evaluated the optical thickness of aerosols in the atmosphere and found that the highest emissions occur in the dry season due to increased fires and a long period of drought.

They also state that the hydrological cycle may be changing due to the emission of large amounts of particles that act as cloud condensation nuclei, and cloud micro-physics properties are being altered. Possibly, these changes in cloud micro-physics may be altering the pattern of precipitation in the Amazon and Pantanal region, leading to the occurrence of high clouds, and the suppression of the formation of shallow clouds (Oliveira et al., 1986; Souza et al., 2020).

ANALYSIS OF TRENDS AND ANOMALY PATTERNS FOR PRECIPITATION LEVELS

The methodology used to calculate the Rainfall Anomaly Index (RAI) was the same adopted by Oliveira et al. (2020) for the State of Mato Grosso do Sul. Figures 6a and 6b show the annual and historical series mean and trends and values of the RAI for CMS and Figures 6c and 6d show the annual and historical series mean and trends and RAI values for stations from TRMM satellite data for the years 1998 to 2019.

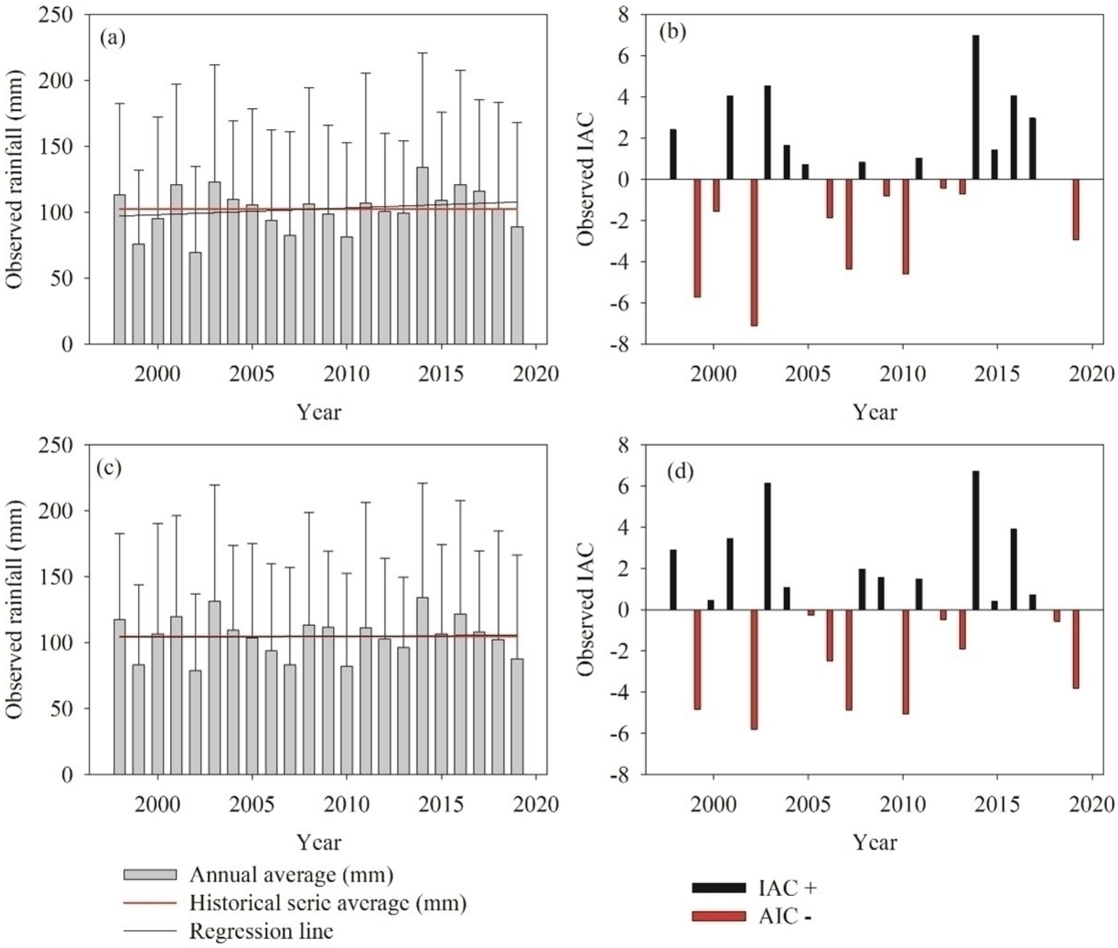

Figure 6 - Annual historical averages of rainfall and standard deviations (a and c) and Rainfall Anomaly Index (b and d) for observed series (a and b) and TRMM series (c and d).

Very low values of rain anomaly correspond to periods of severe drought and the value in the study area ranges from +6.99 in 2014 to -7.10 in 2002. Historical droughts in the wetland coincided with or followed the El Nino events. As shown in Figures 6a, b, c, and d; the precipitation anomaly for these years of drought was considered very low. On the other hand, the regression result indicated that the average annual precipitation decreased by 1.20 mm/every two decades, respectively, and the result was statistically significant at a significance level of 0.05, with maximum values of 1961 mm in the year 2009 and a minimum of 919 mm in the year 2017 (Figures 6a and c).

On the multi-annual scale, even though the Pantanal presents a more humid pattern, events of intense floods, as in the years 1988, 2014, and 2016, interspersed with severe droughts, as in the years 1999, 2002, 2007; 2010, and 2019. This dynamic draws attention to the pace of this variability in terms of frequency and intensity and its effects on the daily lives and territories of the Pantanal populations (Figures 6b and d).

When the amount of rain in the last decades (1998–2019) is compared with the first and second decade, a dramatic reduction in the annual average is observed. For example, the average annual rainfall in the study area from 1998 to 2008 was 1397 mm with a maximum of 1617 mm and a minimum of 1132 mm and for the second decade of 2009 to 2019, the average values were 1364 mm with a maximum of 1692 and a minimum of 919 mm. This means that the average annual rainfall in the wetland has decreased by an average of 1.10 mm in the first decade and by 47.4 mm in the second decade, which means that in the past two decades the rainfall regime in the wetland has been decreasing (Figures 6a and c).

In Figures 6a, b, c, and d, it is also possible to identify years that showed precipitation within the standard deviation of the series, years with normal precipitation and years that were under the influence of the El Niño-Southern Oscillation (ENSO) climate variability mode, both in its positive and negative phase. The ENSO climate variability mode classification in years with annual precipitation totals within the series standard deviation: 1999; 2000; 2001; 2007; 2008; 2010 and 2011 - La Niña and the years: 2002; 2005; 2007; 2009; 2010 - El Niño. It is possible to perceive that the adoption of the series standard deviation as a method of verifying the influence of ENSO in annual rainfall totals for the Pantanal cannot represent, with great precision, the variability of the ENSO, especially in relation to the years with low volumes annual precipitation (negative phase of the ENSO). Climatic anomalies can last for several months, mainly in the tropical atmosphere, and are not only characterized by the lack or excess of some meteorological element but also imply a change in their temporal and spatial distribution. Thermodynamic disturbances that occur in the atmosphere affect the climatic patterns of each region and, consequently, there is a direct dependence on activities with meteorological phenomena belonging to various spatial scales. On a global scale, the greatest influence is due to the climate variability of ENSO and its different phases/intensities (El Niño -EN; La Niña -LN), which are closely related to climate changes, atmospheric circulation and ocean configurations –atmosphere, interaction in the Pacific and Atlantic oceans (Limberger and Silva, 2016; Lyra et al., 2017), thus determining anomalies in air temperature and especially precipitation in various regions (Gonzalez et al., 2013; Gois et al., 2015; Oliveira-Junior et al., 2017).

CONCLUSION

It is concluded that the results found for product 3B43 V7 indicated that the precipitation estimates were representative when compared with the surface observations.

Regarding the estimated monthly precipitation, it was possible to conclude that there is variation between the years according to the data analysis. However, the greatest variations occurred in the rainy season, due to the large rainfall volumes in this period. On the other hand, in the dry period, there were no great variations, because in this period the occurrence of precipitation was more homogeneous.

The precipitation estimated by product 3B43 correctly detected the months with rain for the analysis of the annual period. However, from the analysis of rainy and dry periods, the results showed that in the rainy season the 3B43 V7 product showed a tendency to underestimate precipitation and in the dry period the product trend was to overestimate precipitation.

Even with this difference between the rainy and dry periods, the performance and efficiency evaluation rates of the product were better compared to the 3B42 product. Therefore, it is concluded that when increasing the precipitation accumulation period to a monthly scale, the temporal errors are compensated so that the accumulated total is closer to that observed on the surface.

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