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Influence of climatic phenomena on rainfall in the Tapajós River Basin

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Abstract

Climate change results in weather phenomena such as those that are currently being observed, affecting precipitation, possibly more intensely in the Amazon region. This research is justified by the scarcity of climate risk mitigation measures in the Amazon. Rainfall data from 1992 to 2021 were analyzed, revealing long occurrences of dipole anomalies for consecutive months. Based on the climate indices, the best correlation results occurred in the years with high rainfall, coinciding with the occurrence of negative dipole and of La Niña. Therefore, climate indices can indicate the possible predictive capacity of extreme rainfall events. The results show that the influence of climatic phenomena is more pronounced in the northern region of the Tapajós River Basin.

Keywords: Rainfall. ENSO. Correlation. Dipole.

Introduction

Since the first report of the Intergovernmental Panel on Climate Change (IPCC), released in 1990, society has been alerted to the socioenvironmental problems caused by climate change worldwide. Each new report by the IPCC, reinforce such alerts, but it is clear that these issues have received little attention in Brazilian public education policies. As a result, in addition to the direct consequences for society, there is a lack of public awareness of a fundamental right: "Everyone has the right to an ecologically balanced environment" (BRASIL, 1988, art. 225). Therefore, it is essential to maintain ecological and climatical balance of the environment to guarantee a dignified life for all members of society (FARIA; RAMOS; COLTRI, 2021).

Changes in rainfall—and consequently in river flows—stand out as the most alarming climate transformations. Generally, these changes expose the population to various risks, such as floods that result in deaths and loss of material goods, insecurity caused by erosion that compromises infrastructure works, and contamination of drinking water supply (HOBBIE, GRIMM, 2020).

Climate change has resulted in an increase in the intensity and frequency of climatic phenomena, which affects precipitation, both directly or indirectly. The climatic influences or natural processes that affect rainfall are known as the El Niño Southern Oscillation (ENSO). ENSO originates in the Pacific Ocean and impacts the global climate in different ways. It results from anomalous interactions between the atmosphere and the ocean, occurring irregularly in the equatorial region of the Pacific Ocean. It involves the warming of bodies of water and the action of the trade winds, accumulating warm water on the western side of the Pacific Ocean (ZHANG; SPRINTALL; ZENG, 2021; ANDRADE, 2011).

During the El Niño (EN), the related trade winds are weakened or change their direction at the surface, resulting in warm water remaining over practically the entire Pacific Ocean (JOHARI et al., 2021; OLIVEIRA; MARCUZZO; BARROS, 2015; SILVA et al., 2015). In turn, the La Niña (LN) phenomenon is characterized by an abnormal cooling of the surface water of the

Equatorial Pacific Ocean. Its occurrence is related to changes in atmospheric pressure, especially with the increase in pressure over the Eastern Pacific and the decrease over the Western Pacific. This pressure difference influences wind patterns, resulting in more intense trade winds that originate near the latitude of 30° (ATAÍDE et al., 2022; FREIRE; LIMA; CAVALCANTI, 2011).

The Atlantic dipole is another anomaly that significantly impacts the positioning of the Intertropical Convergence Zone (ITCZ). This anomaly originated from the difference in temperature between the northern and southern regions of the Equatorial Atlantic Ocean: for example, when the North Tropical Atlantic warms up, the ITCZ tends to move towards that region, reducing the rainfall in the Amazon region. On the other hand, if the Sea Surface Temperature (SST) increases in the South Equatorial Atlantic—compared with the North—, this leads to heavier rainfall in the south (FU et al., 2001).

Tropical forests are highly vulnerable to climate change, which threatens their biodiversity, as well as the traditional communities and other groups that depend on them for their livelihoods. In addition, climate change jeopardizes the environmental services that forests provide to both nearby and distant regions (FEARNSIDE, 2008).

In recent decades, the Amazon has suffered more intensely from the lack of infrastructure, technical planning and public policies aimed at mitigating climate risks, and climate variability strongly influences the components of the hydrological cycle (NOBRE; SAMPAIO; SALAZAR, 2007; COSTA; BLANCO; OLIVEIRA-JÚNIOR, 2021). This study made it possible to analyze extreme events based on the occurrence and intensity of climatic phenomena, identifying trends in variability, which can help decision-makers in the region establish preventive or remedial actions.

Therefore, the study aimed to analyze the influence of climatic phenomena on rainfall in the Tapajós River Basin (BHRT), the intensity of the ENSO phenomena and its relationship with rainfall, and the determination of the phases of the inter-hemispheric gradient in the Equatorial Atlantic and its relationship with rainfall. It also aimed to calculate the correlation between rainfall and climatic indices and to verify, based on the results, in which area of the BHRT a given phenomenon has or had the most influence.

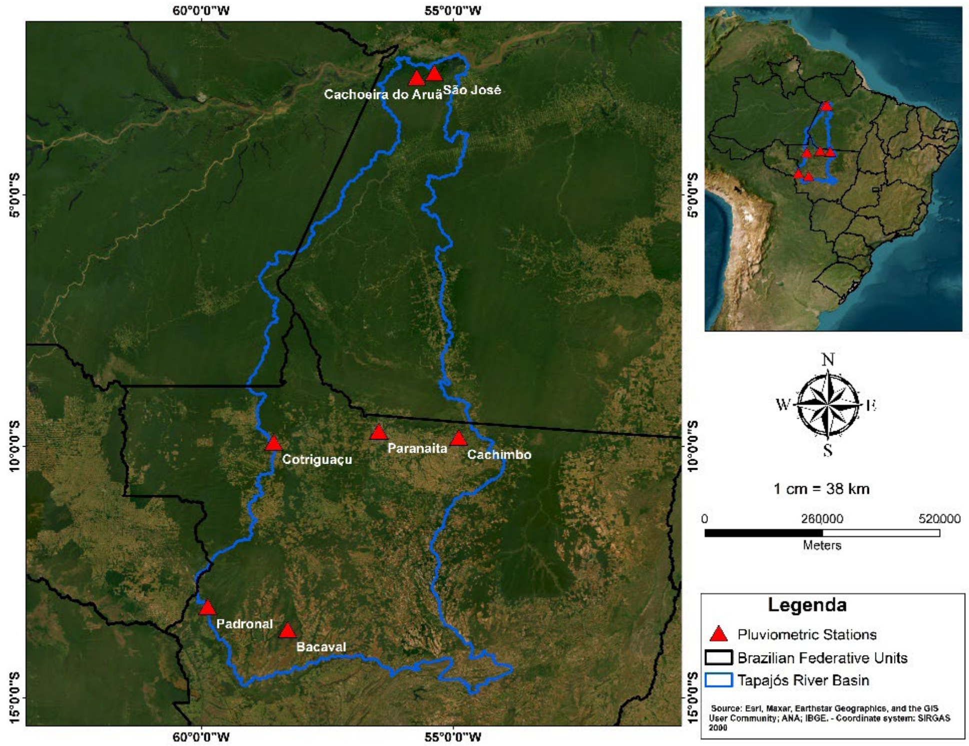
Material and methods

Study area and rainfall data

The BHRT has a drainage area of 493,200 km^2, covers 6 % of the Brazilian territory and is located in the states of Pará (PA), Mato Grosso (MT) and a small part of the state of Amazonas (AM). The main tributary rivers of the Tapajós are the Juruena and Teles Pires (ANA, 2022). Due to its extension, the BHRT has two Köppen-Geiger classifications (KOTTEK et al., 2006): from the headwaters to the center, the predominant climate is classified as “Aw,” i.e., rainfall in summer, a climatic characteristic of savannah regions; from the center to the mouth, the climate is classified as “Am,” a tropical monsoon climate, with a dry season and intense rainfall during the rest of the year, characteristic of the Amazon biome. This is why the study of the basin is so important and strategic: it makes it possible to capture the potential impacts on two different Brazilian biomes (Amazon and *Cerrado*) and their transition. Figure 1 shows the location map.

The data from the rainfall stations studied were collected from the database of the National Water Agency (ANA, 2022), via Hidroweb, and from the Brazilian National Institute of Meteorology (INMET, 2022), via the INMET Meteorological Database (BDMEP), selecting all stations with historical series available with at least 10 years of accumulated data, containing mainly the most recent years, and without gaps. Table 1 shows the stations and periods studied.

Figure 1. Location map of the Tapajós River Basin and the stations studied.



Source: Prepared by the authors, 2023.

Table 1. Description of the stations and data collection period.

Station	Code	Period
Cachoeira do Aruã	255001	1997/2021
São José	255002	2004/2021
Cachimbo	954001	1992/2020
Paranaíta	956002	1999/2020
Cotriguaçu	958004	2004/2020
Bacaval	1358001	1992/2020
Padronal	1359000	1992/2021

Source: Prepared by the authors, 2023.

ENSO climate indices

Data on the Oceanic Niño Index (ONI) were collected from the Climate Prediction Center (CPC) and the National Weather Service, managed by the National Oceanic and Atmospheric Administration (NOAA, 2022). The ONI identifies SST anomalies in the Pacific Ocean using a three-month moving average; thus, the anomalies were classified and analyzed in terms of their occurrence and intensity

Table 2. Classification of the intensity of ENSO phenomena based on ONI.

Classification	El Niño (°C)	La Niña (°C)
Strong	≥ 1.5	≤ 1.5
Moderate	1 to 1.4	-1 to -1.4
Weak	0.5 to 0.9	-0.5 to -0.9
Neutral	-0.4 to 0.4	-

Source: Golden Gate Service, 2022.

according to the criteria presented by the Golden Gate Service (Table 2). A general table of the frequency with which anomalies occurred was also developed. Note that the respective years are considered to be El Niño or La Niña, after five consecutive months, when the aforementioned classification is applied.

Calculation of the inter-hemispheric gradient

The phases of the inter-hemispheric gradient (IHG) of SST in the Tropical Atlantic Ocean (positive/negative dipole) were determined based on the difference between the Tropical Northern Atlantic (TNA) and the Tropical Southern Atlantic (TSA). The monthly TNA and TSA indices are also provided by NOAA (2022), which are located above and below the equatorial line of the Atlantic Ocean.

The criterion for the occurrence of a dipole, i.e., for determining the phase of the gradient, was similar to that used by Souza, Kayano and Ambrizzi (2005). In years in which the IHG (positive/negative) has consecutive values (in at least four months) equal to or above 0.2 °C, dipole is classified as positive; and when it has values equal to or below −0.2 °C, dipole is classified as negative.

Pearson correlation and linear regression

A Pearson correlation analysis and a regression analysis were conducted to examine the relationship between the sum of the monthly rainfall in the stations in each year and the monthly ONI in the annual periods. Analyses were also carried out between monthly rainfall and monthly IHG values at annual intervals to assess the degree of association between these two variables.

Using Pearson's statistical equation (Equation 1), it was possible to determine the magnitude of the correlation between two variables that are on a metric scale (interval or ratio), whose variation ranges −1 (perfect negative correlation) and +1 (perfect positive correlation).

$$R = \frac{\sum(Xi - \overline{X}) \times (Yi - \overline{Y})}{\sqrt{\sum(Xi - \overline{X})^2 \times \sum(Yi - \overline{Y})^2}} \quad [1]$$

In Equation 1, the linear correlation coefficient, represented by "r," estimates the relationship between variables X and Y. To perform this estimation, a sample containing "n" values of X (Xi) and "n" values of Y (Yi) must be available. In other words, for every Xi value in X, there is a corresponding Yi value in Y.

The assessment adopted in this study to measure correlation was based on the method by Dancey and Reidy (2006), who established a weak correlation for values ranging 0.10–0.39, a moderate correlation from 0.40 to 0.69 and a strong correlation from 0.70 to 1.

Results and discussion

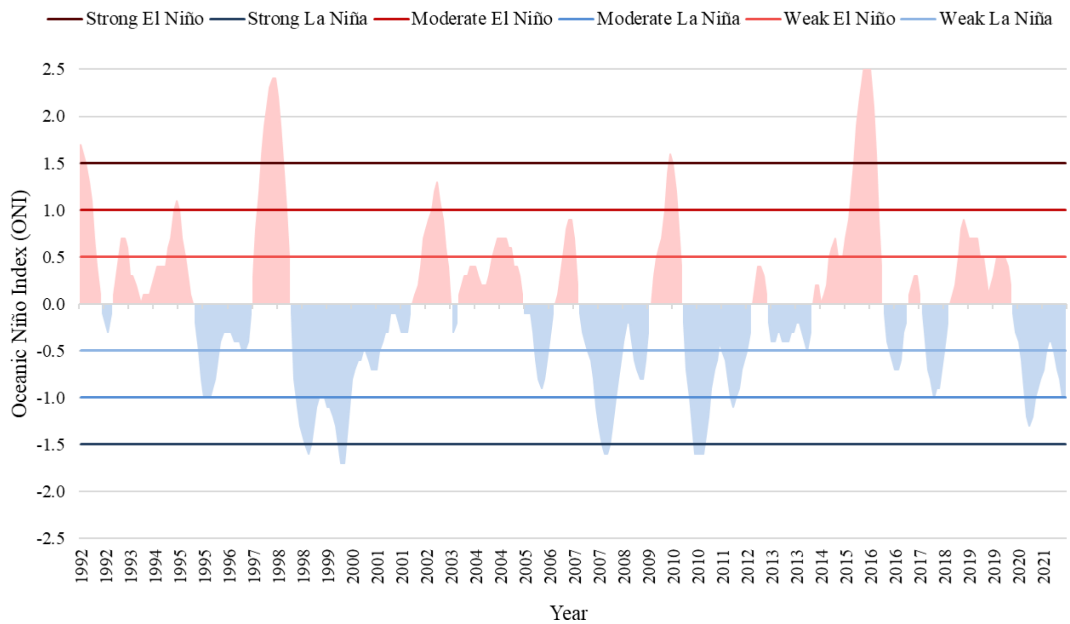
Classification of ENSO events

Figure 2 shows the sequence of events over the time period analyzed, as well as the incidences of ENSO during this period. It is noticeable that, of the 30 years studied, two (1993 and 2013) were considered neutral and in the other 28 there were EN and/or LN events. In seven years of EN and three years of LN, events classified as strong intensity occurred, with 1998 and 2010 being classified as having strong EN and LN, as they began with one event and ended with another. The years 1994 and 2002 were classified as having moderate EN, and 1995, 1999, 2011, and 2020 were classified as having moderate LN. The other years were distributed in the low intensity classes (seven in EN and 10 in LN).

The shortest duration for EN events was five months (September 2006 to January 2007), with consecutive months of low intensity. For the years in which LN occurred, the shortest duration was also five months (November 2005/2008 to March 2006/2009), with low intensity. The longest duration of EN events was 19 months (October 2014 to April 2016) and the longest duration of LN events 32 months (July 1998 to February 2001), both classified as strong intensity.

Table 3 shows a summary of the years in which EN and/or LN occurred, with their respective intensities. In EN years, rainfall is expected to decrease and in LN years, rainfall is expected to increase.

Figure 2. Occurrence of the ENSO phenomenon from 1992 to 2021.



Source: Prepared by the authors, 2023.

Table 3. Summary of the classification of ENSO events.

El Niño			La Niña		
Strong	**Moderate**	**Weak**	**Strong**	**Moderate**	**Weak**
1992, 1997, 1998, 2009, 2010, 2015, 2016	1994, 2002	2003, 2004, 2005, 2006, 2014, 2018, 2019	1998, 2007, 2010	1995, 1999, 2011, 2020	1996, 2000, 2001, 2005, 2008, 2009, 2012, 2017, 2018, 2021

Source: Prepared by the authors, 2023.

Phases of the inter-hemispheric gradient (TNA-TSA)

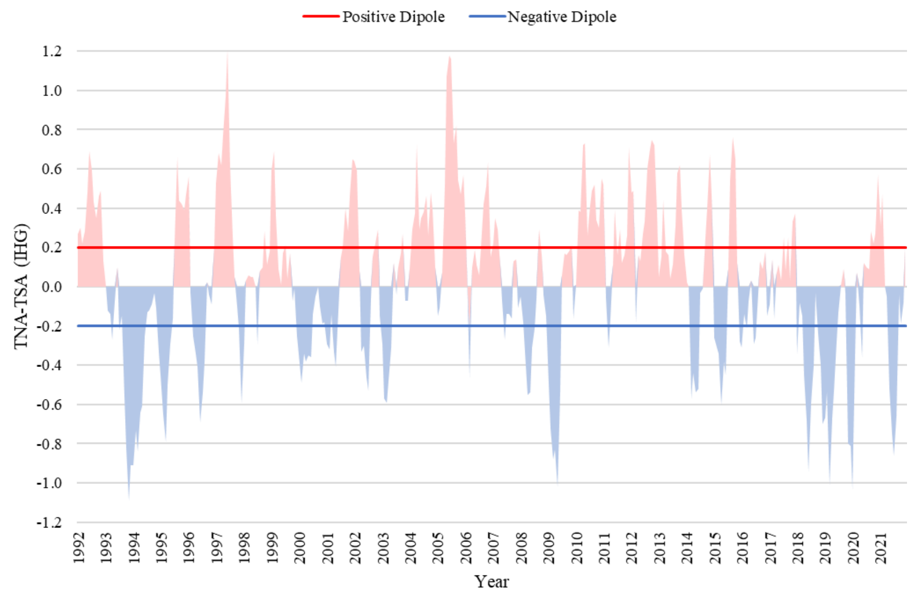
Figure 3 shows the disposition of the gradient between the hemispheres over time and the criteria established to classify dipole as positive or negative. It was found that dipole anomalies (positive, negative or both) occurred in 23 of the 30 years in the series.

The shortest interval in which positive dipole anomalies occurred was four months, specifically in 2006, 2013 and 2014. As for the longest duration of positive dipole anomalies, the maximum value observed was 12 months during the 2010/2011 period. For negative dipole anomalies, the maximum duration recorded was 10 months, from 1993 to 1994.

Table 4 summarizes the years in which the anomalies occurred. In total, 12 years with the presence of negative dipole were recorded, six of which also showed LN phenomena (1995, 1996, 2000, 2008, 2009 and 2018). In total, there were 11 years with the presence of positive dipole, four of which also had EN phenomena (1992, 1997, 2002 and 2004).

During 1992 and 2010, some of the longest occurrences of positive dipole anomalies were recorded, with a consecutive duration of 11 months. Notably, these periods coincided with years of strong EN influence. According to Sousa, Santos and Costa (2022), the 2007/2008 period saw the intense occurrence of La Niña, as well as the presence of negative dipole, coinciding with the result found for the same years.

Figure 3. Inter-hemispheric gradient (TNA-TSA) from 1992 to 2021.



Source: Prepared by the authors, 2023.

Analysis of the correlation between rainfall and climate indices

Rainfall x ONI

In this study, the months of different years at each station were analyzed (Table 1). Figures 4 and 5 show the monthly analysis of the years with a strong correlation level and strong EN or LN, compared to the ONI values. Note that among the years with a strong correlation, there were also ENSO events classified as strong in intensity, and this criterion was used to create the graphs.

The graph of monthly averages for the Cachoeira do Aruã station in 1998 (Figure 4) shows that May, September, October and November were below the monthly mean for the analyzed year. It should be noted that these same months were subject to strong LN according to the classification, which may have influenced this issue. The monthly average for 2000 was above the general monthly average in most months, and there was only one period of LN in the year, which ranged from weak to strong.

Table 4. Summary of the years of the classified anomalies in the Tropical Atlantic.

Negative dipole	Positive dipole
1993, 1994, 1995[1], 1996[1], 2000[1], 2003, 2008[1], 2009[1], 2014, 2015, 2018[1], 2019	1992[2], 1995, 1997[2], 2001, 2002[2], 2004[2], 2005, 2010, 2012, 2020, 2021
[1]La Niña years	[2]El Niño years

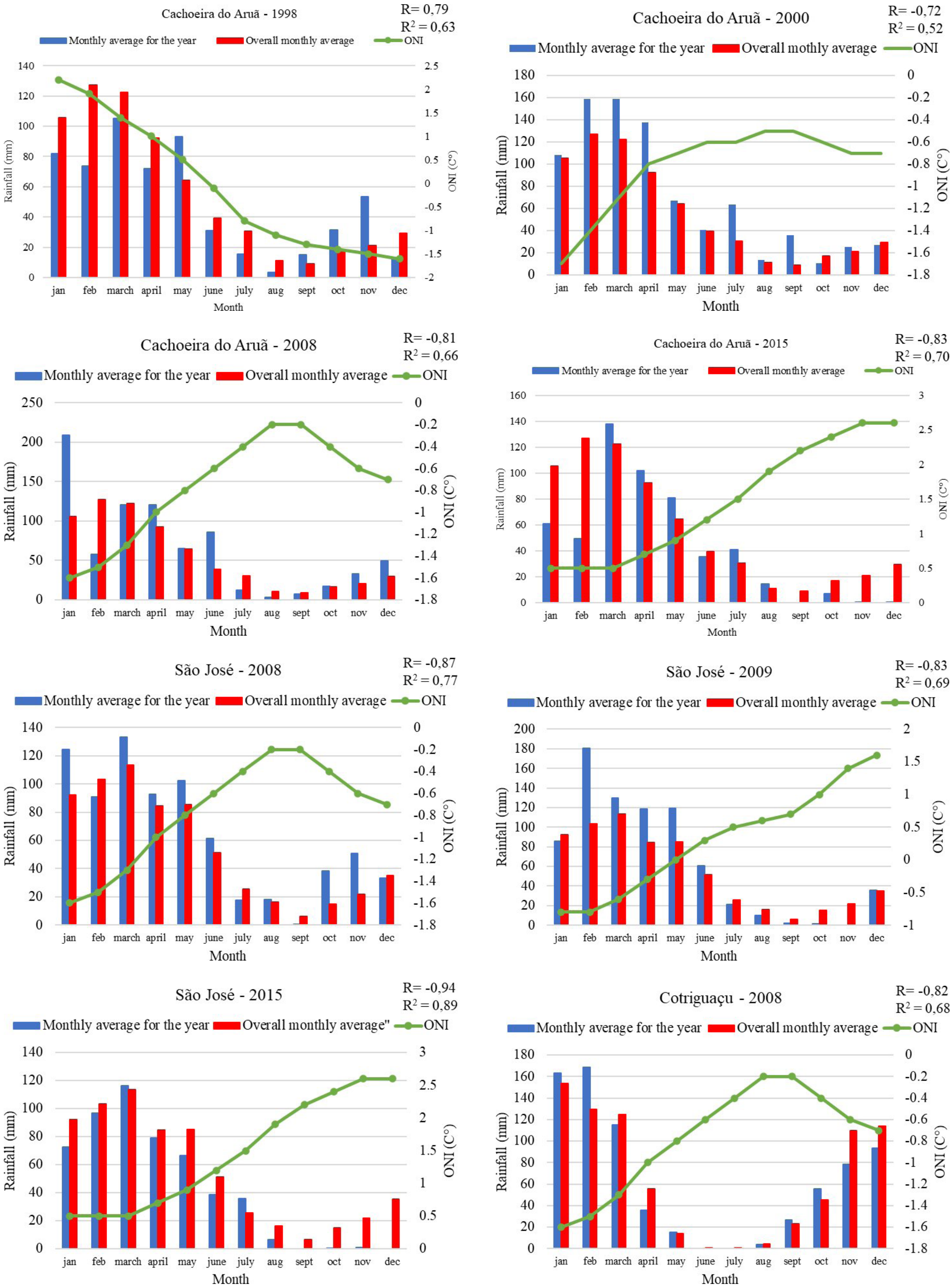
Source: Prepared by the authors, 2023.

Santos, Blanco and Oliveira (2019) stated that, for the Cachoeira do Aruã station, the period with the highest probability of rain comprises the months of January to June, and the period with the lowest probability of rain comprises the months of July to December, which coincides with the results found in this study.

For 2015, it can be seen that the level of precipitation decreased, which may have been due to the occurrence of an EN event in all months of the year, with greater intensity (strong) from August onwards. Figure 4, referring to the Cachoeira do Aruã station, shows that the level of precipitation decreased in the monthly average of 2015 from August onwards.

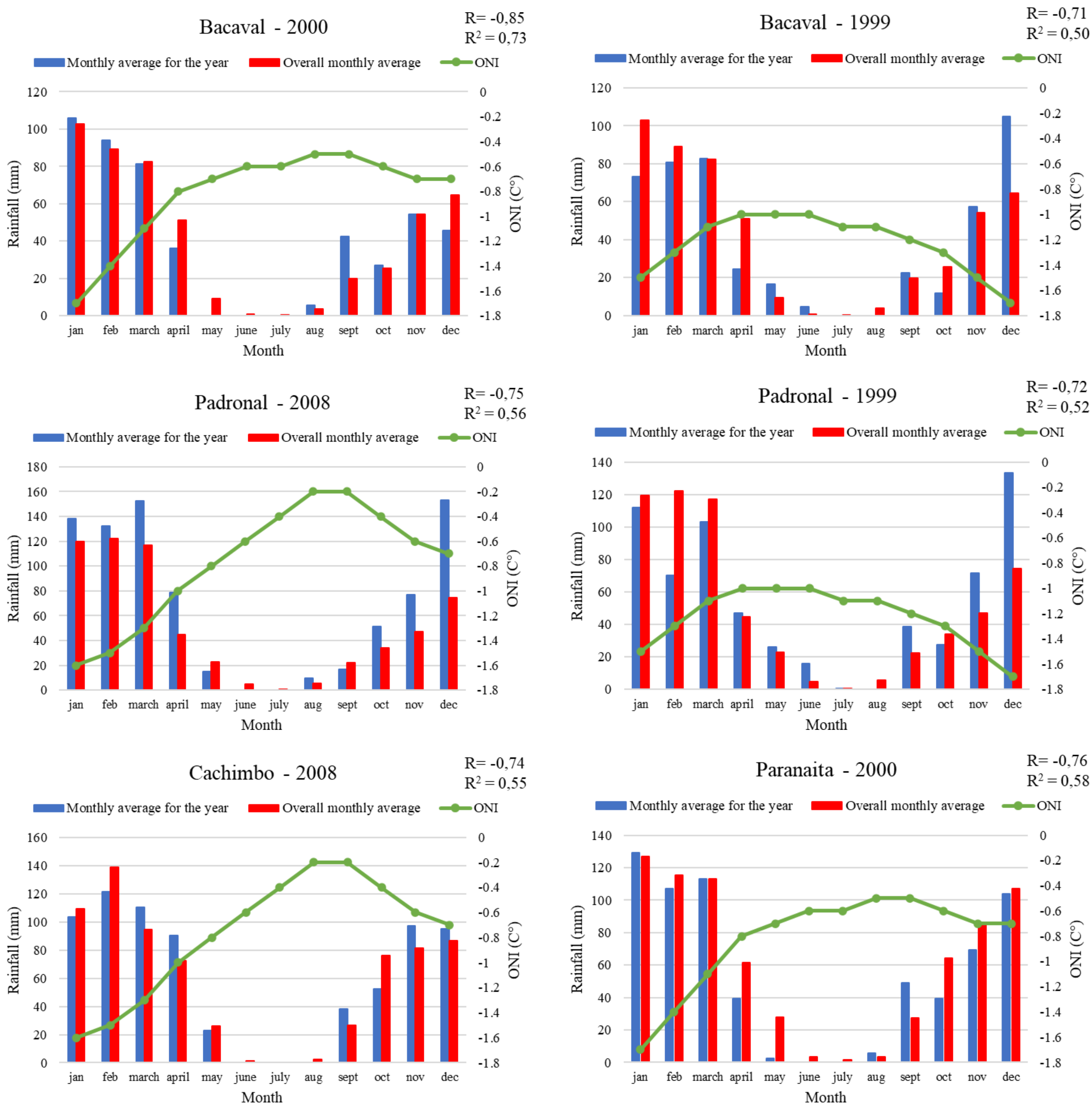
In 2008, the monthly average level for the São José station was above the general average

Figure 4. Comparison between ONI and average monthly rainfall for the years with a strong correlation.



Source: Prepared by the authors, 2023.

Figure 5. Comparison between ONI and average monthly rainfall for the years with a strong correlation (continued).



Source: Prepared by the authors, 2023.

(Figure 4). In the same year, most months were classified as having LN events, while July, August and September were classified as neutral, which explains the low level of precipitation. The first few months of 2009 were classified as having LN events, with the level of precipitation decreasing from July to December, and according to the classification of ENSO events, only EN events occurred in these months.

For the Paranaíta station (Figure 5), it can be seen that, from the year 2000 onwards, rainfall was low in the months of June, July and August. The years of strong correlation of this station for these months were low in the classification of ENSO events, being classified as having neutral or weak LN. Figure 5 shows that for the Padronal station, the months of January, November and December 1999 were classified as having strong LN. In these months, the average rainfall was close to and even above the general monthly average.

In 1999, the Bacaval station had practically the same pattern as the Padronal station, which may have been because they are located very close to each other, to the south of the BHRT, as shown in Figure 1. In turn, for the year 2000, rainfall was above the general monthly average in the first few months. According to the classification of ENSO events, these months have strong to moderate LN, while the months of May, June, July and August have weak LN (Figure 5).

For 2015, the Cachoeira do Aruã and São José stations had the highest R and R^2 values, and this was considered the year with the longest duration and permanence of an EN event, classified as weak to strong and extending into 2016. It is worth noting that the two stations are located very close to each other, to the north of the BHRT. According to Costa and Blanco (2018), high correlation adjustments based on climate indices may indicate an ability to predict extreme rainfall events.

When analyzing the results found according to each station studied in the various locations of the basin and their respective years, it can be seen that the influence of ENSO events is stronger in the northern region of the BHRT.. Most of the years with high rainfall were classified as having LN, while the years with low rainfall were classified as having EN, standing out from the other stations located in the different areas of the basin.

It is worth noting that the Cachoeira do Aruã station, for example, located in the north of the basin, had strong periods of EN during the months of January, February, March and April 1998. When this phenomenon occurs, the northern region usually experiences an increase in rainfall, while the southern region can have drier periods. On the other hand, strong periods of LN were observed in 1999 for the Padronal station in the south of the basin. During this phenomenon, the northern region tends to have drier periods and the southern region can be subject to more rain. These seasonal variations are fundamental to understanding the climatic dynamics of the region and can have significant impacts on water and environmental management.

Rainfall x IHG

Figure 6 shows a comparison of the monthly average of the years and the overall monthly average, taking into account the years of strong correlation/strong ENSO events and comparing the IHG values as well.

In the first few months of 2000, the Cachoeira do Aruã station recorded more rainfall than the overall monthly average (Figure 6). According to Table 4, the year 2000 was classified as having negative dipole. For the São José station, in 2009, the monthly average rainfall was above the general monthly average from January to June, which may have been influenced by the dipole, since the months mentioned above were classified as negative dipole, and it can be seen that negative dipole no longer occurred from July onwards (as shown in Figure 6 and Table 4). For the year 2015, the monthly average was slightly below the overall monthly average, as the years with a strong correlation in this station had higher rainfall rates, there was a decrease in rainfall in the months of August, September, October and November, and these months were classified as having positive dipole. In January, however, there was an increase in the index, due to the influence of the negative dipole that occurred in the month.

For 2007—Cachimbo, Paranaíta and Cotriguaçu stations—and 2005—Cotriguaçu station—a pattern can be seen in the months of May, June, July and August, when rainfall was low. When analyzing the ENSO events and the classification of the dipoles, the influence of these phenomena on these years/months becomes clear, as they were classified as neutral months

Figure 6. Comparison between IHG and average monthly rainfall for the years with a strong correlation.

Source: Prepared by the authors, 2023.

for ENSO events and as having positive dipole (2005) and weak LN (2007).

In 2009, the São José station recorded the highest values of R and R^2, which can be attributed to the fact that this year had one of the highest averages for the negative dipole anomaly. In addition, there was no interference from ENSO, since the EN event occurred at the end of the year and lasted until 2010. Oliveira et al. (2020) defined the following hydrological period for the Tapajós River in Santarém/PA (Cachoeira do Aruã and São José stations): high tide (April to June), ebb tide (July to September), drought (October to December) and flood (January to March). This definition is consistent with the figures presented, with high rainfall in the first months of the year and low rainfall in the last months.

Conclusions

The influence of ENSO on precipitation levels in the BHRT became clear, with an increase in rainfall during LN years. Most of the years with strong R and R^2 correlations coincided with the occurrence of LN. Regarding the anomalies in the Equatorial Atlantic, in the years in which strong correlations were recorded, there was negative dipole, which leads to the conclusion that this phenomenon may have more influence on rainfall, especially when it coincides with LN years. It was also observed that the influence of ENSO events is stronger in the northern region of the BHRT.

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