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GEOSCIENCES

Analyzing the inter-annual variability of rainfall in the Brazilian semi-arid region

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ABSTRACT. This research aims to analyze the interannual variability of rainfall and the correlation between solar cycles and teleconnections with the precipitation regime of the Intermediate Geographic Region of Caicó (IGRC), in the semiarid region of the state of Rio Grande do Norte, northeast Brazil. For the analyses, three time-series were used, 1913 to 2020 for the relationship between rainfall and sunspots; and both 1950 to 2020 and 1982 to 2020 for the relationship between rainfall and teleconnections (El Nino Southern Oscillation – ENOS, Atlantic Dipole and sunspots). For the data analysis, basic statistical techniques, nonparametric statistical tests such as the Mann-Kendall and the Pearson correlation coefficient were used. Results have shown that the correlation between sunspots and rainfall was -0.2, indicating a weak negative correlation (1913-2020), with a confidence level of 95%. For rainfall and ENSO (Niño 1+2 and Niño 3) it was 0.4, with a 99% confidence level for Niño 1+2, 0.3 for Rainfall and North Atlantic (TNA), and 0.3 for sunspots and rainfall with a 95% confidence level (1982 to 2020). There was no trend in rainfall values in the last century. It was concluded that the patterns of sunspots, ENSO, and the Atlantic dipole were correlated with precipitation levels in the IGRC, and studies on teleconnections and extraterrestrial factors need to be further explored to try to understand the genesis of rainfall in various parts of the globe.

Keywords: rainfall; sunspots; el nino southern oscillation; atlantic dipole; brazilian semiarid region.

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Introduction

Climate changes are conditioned by recent temporal and/or spatial variations in temperature. These changes are determined by the energy balance in the Earth-atmosphere system. Therefore, any changes in this balance directly affect the variation in air temperature, winds, and, consequently, rainfall (Intergovernmental Panel on Climate Change [IPCC], 2021). The temperature depends on how the atmosphere responds to the energy balance, but atmospheric characteristics are dynamic and vary in time and space, from macro to micro scales. Changes can be understood in two aspects, in the Earth-Atmosphere system and extra-atmospheric conditioning factors (Rigozo et al., 2008, Ynoue, Reboita, Ambrizzi, & Silva, 2017). Among these extra-atmospheric factors that influence climate changes, solar activity should be highlighted, as there is a close relationship of interaction between solar energy and the atmosphere of the planet. One must understand the importance of the energy from the Sun as a condition of the Earth-atmosphere system, since this star is the main energy supplier for the surface of the planet, responsible for more than 99% of the energy that is used for various purposes in this system. In general, oceans also play a very important role within the climate system since they are interconnected to both dynamic and thermodynamic processes that are part of the complex interaction between oceans and the atmosphere (Hartmann, 1994, Ynoue, Reboita, Ambrizzi, & Silva, 2017). Research suggests that there is an association between the variability of the atmospheric climate and ocean conditions, which is explained by the high thermal capacity of the water, represented by seas and oceans (Tremberth, 1997, Molion & Oliveira, 2008). Therefore, it is to be expected that the oceans assume the role of a "modulator" of the global climate (Siqueira, Nery, & Carfan, 2023). Thus, it can be assumed that the variation in Sea Surface Temperature (SST) plays the role of an atmospheric force (Bjerknes, 1969, Hoskins & Karoly, 1981, Müller & Ambrizzi, 2007). Regarding the correlation between the Sun and oceans, scientific studies have shown the influence of solar activity on the climate of the planet, including on teleconnection patterns. Malik (2017) and Malik et al. (2020), bring a literature review on the influence of the sun on ocean-atmosphere teleconnections that occur in the Pacific (El Nino Southern Oscillation - ENSO) and Atlantic

(Atlantic Multi-decadal Oscillation - AMO) oceans, showing a correlation between solar activity and their intensity and duration. According to other researches (Marsh & Svensmark, 2000, Roy & Collins, 2015), it can be considered that having a decrease in cloud cover during maximum solar activity will allow a greater amount of solar radiation to reach the oceans, thus contributing to its heating and consequently a greater number of El Niño events. Since ENSO an the Atlantic dipole are teleconnection patterns that directly influence the rainfall in the semi-arid region of Brazil, as already proven in several studies included in the references of this work, such as Ferreira and Mello (2005), Silva and Galvíncio (2011), Costa et al. (2020a) and Medeiros and Oliveira (2021), we have aimed at analyzing the correlation between solar cycles, ENSO, the Tropical Southern Atlantic Index (TSA), and the Tropical Northern Atlantic Index (TNA) teleconnections with the rainfall regime of the Intermediate Geographic Region of Caicó (IGRC), in the semiarid region of the state of Rio Grande do Norte. Solar cycles and teleconnections were characterized as explanatory variables, and rainfall as a response variable, to verify the relationship between the variation that exists in the total annual rainfall in this region, and the extraterrestrial and oceanic conditioning factors.

With this information, it is coherent to assume that there may be some relationship between the solar cycles, ocean temperature, and atmospheric events present on the planet, more specifically in terms of rainfall. Thus, it is understood that there is a need to collect and analyze data on solar activity, ocean thermal conditions, and the climate to better comprehend the rainfall regime in the semiarid region and, with it, establish strategic plans for the implementation of specific actions in the municipalities comprised in the Intermediate Geographic Region of Caicó (IGRC) and other neighboring locations of the Brazilian semiarid region.

Study area

The Intermediate Geographic Region of Caicó (IGRC) is one of the three intermediate regions that make up the state of Rio Grande do Norte. Located in the inland portion of the state, it comprises 24 municipalities, an area of 9,371 km² with an estimated population of 297,188 inhabitants. In the IGRC, of the 24 municipalities only three have climatological stations with historical series greater than or equal to 30 years: Caicó, Cruzeta, and Florânia (Figure 1). Caicó is the most populous, with estimated 67,554 inhabitants and an area of ~1,228 km². Cruzeta, in turn, has an estimated population of 7,998 inhabitants, and an area of 295 km²; and Florânia has an estimated population of 9,116 inhabitants and an area of 504 km² (Instituto Brasileiro de Geografia e Estatística [IBGE], 2017).

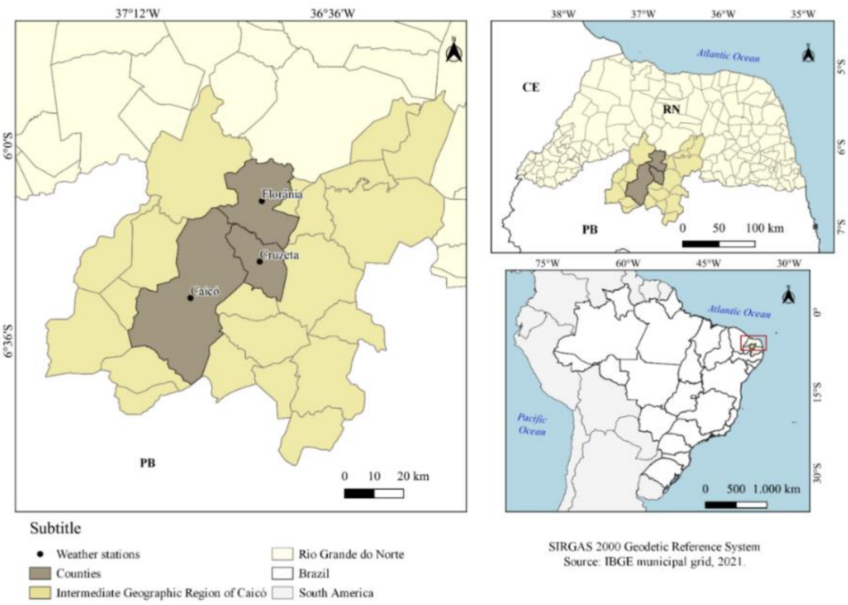

Figure 1. location map of the study area: Brazil, state of Rio Grande do Norte, intermediate geographic region of Caicó, and the municipalities of Caicó, Cruzeta, and Florânia. Source: Elaborated by the authors

The climate of the IGRC, according to the Køppen Climate Classification (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013), is of the Bsh type, hot semi-arid with a markedly dry season, presenting itself as one of the hottest and driest climates in the Brazilian Northeast (Silva, Santos, Santos, & Lucena, 2022). The historical rainfall series of the region shows that the mean annual rainfall varies between the median and the lower quartile, with mean values around 603 mm and the maximum, average, and minimum temperatures are high throughout the year, remaining at around 30°C (Lucena, Santos, Ferreira, & Steinke, 2016). The insolation and evaporation rates are always high and, associated with the crystalline terrain, do not favor the accumulation of water, benefiting the semiarid situation (Ab' Saber, 2003). With the combination of these conditions and the latitudinal location of the municipalities, high air temperature indices and aridity values below 0.50 are generated, classifying the climate of the region as semi-arid (Lucena, Cabral Junior, & Steinke, 2018, Lucena, Silva, Esteca, & Galvani, 2024). The shallow and stony soils favor the development of vegetation of the Caatinga type, rich in shrubs and low trees, in addition to several xerophytic species (Salimon & Anderson, 2018). Figure 2 shows the climograph representing the average historical temperature and rainfall for the municipalities of Caicó, Cruzeta, and Florânia.

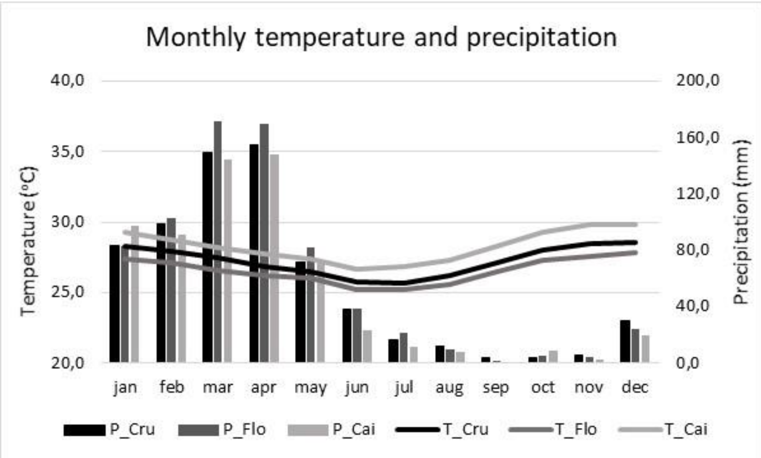

Figure 2. Climograph representing the IGRC, considering the average temperature and rainfall values from 1981 to 2010, with data from the municipalities of Caicó, Cruzeta, and Florânia. Source: INMET data. Elaborated by the authors

As can be seen in Figure 2, there is a strong seasonality in the annual distribution of rainfall, with a dry period of approximately 7 months that occurs in the second half of the year, when temperatures are at their highest. In addition to this significant decrease in rainfall in the dry season, there are years when rainfall is insufficient in the rainy season (first half of the year), leading to hydrological droughts and water crises (Claudino et al., 2021). The semi-arid region of Brazil, where our study area is located, has historically experienced prolonged inter-annual periods of drought (Conti, 2002, Costa et al., 2020a). Droughts and dry spells are recurrent natural events in this region, caused by the predominance of a negative water balance. The economic conditions of the population place them at a high level of vulnerability to these adverse events, causing public calamity and disaster (Tominaga, Santoro, & Amaral, 2009, Alpino, Freitas, & Costa, 2014). This is why it is so important to understand the great inter-annual rainfall variability and the phenomena that influence it.

Materials and methods

Data collection and processing

To conduct this research, it was necessary to collect data on rainfall; sunspots; and ENSO, TSA, and TNA teleconnections.

The collection of monthly and annual rainfall data on Caicó was conducted through rainfall stations of the Agricultural Research Company of the State of Rio Grande do Norte (EMPARN) (https://bitily.me/BmbTg) and the National Institute of Meteorology (INMET), with values from 107 years, from 1913 to 2020. The data from Cruzeta (RN) and Florânia (RN) came from the National Institute of Meteorology (INMET) (https://bdmep.inmet.gov.br/) and the Hidroweb portal, managed by the National Water Agency (ANA) (https://www.snirh.gov.br/hidroweb/serieshistoricas). Precipitation is represented in millimeters. The Pearson correlation was performed to verify the similarity between them, the correlation between the rainfall in Caicó and Cruzeta was 0.9; and, between Caicó and Florânia, it was also 0.9, indicating a strong correlation (Table 1). We, therefore, chose to use only Caicó for the rest of the analysis, because its time series of rainfall data covers a greater number of years and does not contain gaps, different from Cruzeta and Florânia. With a correlation coefficient of 0.9 at a significance level of 0.05, this station represents the regional rainfall regime of the Intermediate Geographical Region of Caicó.

Table 1. Comparative analysis of rainfall (mm) between municipalities in the Intermediate Geographic Region of Caicó. Values of *r* (0.9) with 0.05 significance.

	Caicó	Cruzeta	Florânia
Average	668.1	610.8	632.7
Maximum	1560.5	1545.4	1545.2
Minimum	107.10	96.50	81.6
Amplitude	1453.4	1448.9	1463.6
Standard Deviation	296.0	281.9	296.0
Correlation r =		0.9	0.9

Source: Elaborated by the authors

To identify the years with the rainfall categorized as regular, dry, rainy, very dry, and very rainy we have used the technique of quantiles, which are separators. Next, we obtained the quantile orders and classification into groups (Lopes, Souza, & Ferreira, 2013). For this work, we have used the quantile orders Q0.15; Q0.35; Q0.65, and Q0.85, to establish the classes concerning the observed values (xi) of rainfall (Table 2).

Table 2. Classification of standard years by quantile methods.

Classification	Deviation (+) or (-) in %
Very Dry Years	xi<q0.15
Dry Years	q0.15<xi<q0.35
Regular Years	q0.35<xi<q0.65
Rainy Years	q0.65<xi<q0.85
Very Rainy Years	x>0.85

Source: adapted from Lopes, Souza and Ferreira (2013).

The solar cycles analyzed are the series of annual and monthly values corresponding to the period from 1913 to 2020, obtained from the website of the Center for Analysis of Data on Solar Influences, which is based in the department of solar physics research of the Royal Observatory of Belgium (SIDC, Belgium: http://sidc.oma.be/index.php3) and the Space Weather Prediction Center (NOAA) (https://bitily.me/fjhbC).

Data regarding the occurrence of the El Niño and La Niña phenomena, and the Atlantic dipole, as well as their intensity, were collected on the website of the Weather Forecasting and Climatic Studies Center (CPTEC) of the National Institute for Space Research (INPE - http://www.cptec.inpe.br), covering the period from 1950 to 2020. To verify the occurrence of the meridional or inter-hemispheric SST gradient, also known as the dipole pattern, data were obtained from the Department of Meteorology at the Federal University of Itajubá (Centro de Previsão e Estudos de Tempo e Clima de Minas Gerais [CEPreMG], 2021), using data from HadlSST/NOAA – National Oceanic and Atmospheric Administration (USA). Data on ENSO (Niño 1+2, Niño 3 and Niño 3.4), TSA, and TNA cover the period from 1982 to 2020. Monthly and annual teleconnection values refer to sea surface temperature anomalies (in degrees Celsius).

Data analysis

To analyze the research data, we have obtained measures of central tendency, dispersion, percentage and quartiles; we have used the Shapiro-Wilk normalization test and the Mann-Kendall test for trend detection; and Pearson's, Spearman's, and Kendall-tau correlation analysis and significance analysis were obtained by Student's t-test, as described below. These techniques were chosen because they have been used and validated in several scientific works in climatology (Chairani 2020, Delioglani & Anagnostopoulou, 2023, Chen et al., 2023). The Shapiro-Wilk multivariate normality test was also performed, from the mvnormtest RStudio software package, applying the mshapiro.test function. From this, the normality or not of the data of the two historical series studied was verified, a data series is considered to have normal distribution if $p - value \geq 0{,}05$ and non-normal if $p - value < 0{,}05$. To find the long-term linear trends of both rainfall and sunspot data, we have used the Mann-Kendall test. According to Goossens and Berger (1986), this is the most appropriate method for detecting and approximating the location of the starting point of a certain trend. This statistical test is widely used to check whether the trend is statistically significant or not (equations 1 and 2).

$$S = \sum_{k=1}^{ni-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k) \quad (1)$$

$$\mathrm{sgn}(x) = \begin{cases} +1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases} \quad (2)$$

In equations (1) and (2), S is the Mann-Kendall statistic test, n is the sample size and sgn is the sign of the difference in subsequent values. The test was evaluated considering a significance level of 5%. If S is significantly different from zero, H0 can be rejected for a certain level of significance, while H1 indicates that the existence of a trend is accepted. The linear trend of a series indicates its "long-term" behavior, that is, whether the variable in question increases, decreases, or remains stable over the period being analyzed.

In this research, the Pearson, Spearman's, and Kendall-tau equations for the correlation analysis were also used. The Pearson correlation coefficient is a measure of linear association for the strength of the correlation between two variables (Figueredo & Junior, 2009), making its application, therefore, perfectly viable here, since we have sought the correlation between the total rainfall volumes with the total of sunspots, and the patterns of the Pacific and Atlantic teleconnections. Spearman's and Kendall's non-parametric correlation coefficient tests were also applied to make an association between the positions of the variables (Capp & Nienov, 2020). In a comparative analysis of the correlation tests applied, due to the similarity between the results found, we opted for the one with the best statistical significance, which was Pearson's correlation coefficient (equation 3).

$$\rho = \frac{\sum_{1=1}^{n}(x_i-\bar{x}).(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}.\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} = \frac{\mathrm{cov(X,Y)}}{\sqrt{\mathrm{var(X).var(Y)}}} \quad (3)$$

This coefficient assumes values ranging from -1 to 1. Thus, r = 1 means a perfect positive correlation between two variables; r = -1 means a perfect negative correlation between two variables, that is if one increases the other decreases; r = 0 means that two variables do not linearly depend on each other. The negative r coefficient means an inversely proportional correlation; when r is positive, the correlation is directly proportional. Regarding the interpretation of data, the results are: 0.7 (+ or -) indicates a strong correlation; 0.3 to 0.7 (+ or -) indicates a moderate correlation; 0 to 0.3 (+ or -) indicates a weak correlation. The Pearson correlation analyzes were tested with statistical significance at the level of 0.01 and 0.05, using Student's *t*-test. Correlation analyses were conducted individually between rainfall (a dependent variable) and each of the climatic forcing, such as sunspots, Pacific Ocean surface temperature anomaly conditions, and the Atlantic Ocean surface temperature anomaly conditions (independent variables). A correlation matrix was also created, including all the variables under analysis covering the period 1981 - 2020. The correlation matrices and associated tests were developed in the Jamovi software (version 2.3).

Results

Rainfall x Sunspots

During the analyzed period, from 1913 to 2020, the average value found for rainfall in Caicó was 668.1 mm, the maximum value of the series was 1560.5 mm, in 1974, and the minimum was 107.1 mm, in 1919. Therefore, the amplitude and the coefficient of variation of rainfall were 1453.4 mm and 44.2%, respectively. This result points to a large interannual variation in rainfall, exposing the population and its activities to climatic/rainfall risks, and, therefore, to water vulnerability, since this coefficient can vary by more than 1400 mm from one year to another. This high variability in total annual rainfall is typical of the semi-arid region of Brazil (Ab' Saber, 2003, Sá, & Silva, 2010, Silva & Lucio, 2015). We have obtained the results described in Table 3 by the the Mann-Kendall test for the Rainfall data.

Table 3. Mann-Kendall test results for rainfall data.

Mann-Kendall	
Kendall's tau	0.091
P-Value	0.14
Sample Size	107
Alternative Hypothesis	Exist tendency
Statistical Significance	No Statistical Significance

Source: Elaborated by the authors.

According to the results presented, we have identified a slight increase in rainfall, as we can see in Kendall's Tau (0.091), but as the P-Value (0.14) is greater than 0.05, there is no statistical significance; but the alternative hypothesis, that there is a positive trend, cannot be rejected, as we can see in Figure 3, although it is not significant.

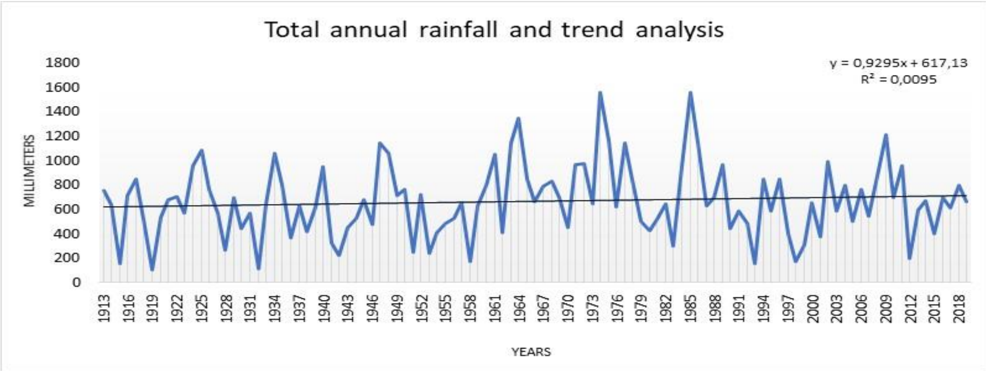

Figure 3. Mann-Kendall Test Chart for Rainfall (mm) for the data regarding the period from 1913 - 2020.

By analyzing the series of sunspots, we have verified that the average amount was 33,012.74, the absolute maximum value found was 98,288 sunspots, in 1957, and the lowest was 876 sunspots, in 1913. The amplitude was 97,412, and the coefficient of variation was 76.5%. These high values of amplitude and coefficient of variation are explained by the fact that the Sun has a well-defined cycle, where the number of sunspots varies considerably from the minimum to the maximum, over a period of approximately 11 years. As we can see from the results, the data from the time series referring to solar activity in the period from 1913 to 2020 did not show a trend, with a very slight amount of reduction in spots (Kendall's Tau = -0.00) without statistical significance, once the P-Value (0.95) was far above 0.05.

Using the Shapiro-Wilk normality test, we have verified that the rainfall historical series obeyed the normality, but, in the series corresponding to the number of sunspots, we have verified that it did not present a normal distribution, since a p-value equal to 1.45x10^(-5) was found. Therefore, it was necessary to normalize the series of sunspots, using the methodology proposed by Curtiss (1943). After this, the Pearson statistical correlation was performed according to each solar cycle x rainfall period. Later, the same correlation was made in the complete historical series, resulting in -0.2, indicating a weak negative correlation between sunspots and rainfall in Caicó. However, in solar cycles 18, 19, 20, and 21, the correlation obtained was moderate, with its maximum value obtained in cycle 21 (1976 to 1986), which was -0.7 (strong correlation). It is important to highlight that, in cycle 21, there were the solar minimums of 1976, 1985, 1986, and strong La Niña events, such as in 1985, where rainfall in Caicó was 1560.5 mm; in Flôrania it was 943.1 mm, and in Cruzeta it was 1199.7 mm annually, but, during the period from 1977 to 1984, there was strong solar activity and low rainfall. After finding the result of r -0.2 for the historical series (1913-2020), solar activity, and rainfall, we have moved on to the second stage of analysis, this time to verify the possible correlation between solar cycles, teleconnections (ENSO and Atlantic dipole) and rainfall at the IGRC.

Solar cycles, teleconnections, and rainfall at the IGRC

Since scientific research has detected correlations of teleconnections such as the El Niño and La Niña (ENSO), and the Atlantic Dipole (TSA and TNA) phenomena with rainfall in the Brazilian semiarid region, we have decided to quantify and qualify their occurrence with the values of rainfall in the Intermediate Geographic Region of Caicó (IGRC), within each solar cycle. The quantification of the studied phenomena that appeared in each solar cycle was performed, but the dipole data were only found from 1950 onwards, which is why the dipole data contained in the Tables (4 - 9) only appears after 1950.

It is possible to see that the greatest amount of El Niños happened during solar cycles 22 and 23, where each had a total of eight events, as well as cycle 20, which had seven events. We can then consider that, after cycle 18, with only three events, there was an increase in the occurrence of El Niños from cycle 19 on, until cycle 24, when there was a decrease. However, in cycle 24, there was an El Niño occurrence, when the National Oceanic and Atmospheric Administration (NOAA) predicted a strong ENSO event during the winter of 2015-2016. This event was called the "Godzilla El Niño" and it was expected that it would be similar to those from 1982/1983 and 1997/98 (Schiermeier, 2015). An explanation for this increase in El Niño events may be related to a decrease in cloud cover during solar maximums, where a greater amount of solar radiation may occur over the oceans, increasing their temperature (Roy & Collins, 2015). Regarding the occurrence of La Niña events, we have verified that the phenomenon did not follow the same increasing trend as the El Niño ones, since the cycle where more La Niña events occurred was during cycle 20, where the total reached seven, and, during cycle 17, there were six. Therefore, the study did not show a clear trend in the occurrence of La Niña events.

As for the occurrence of phases of the Atlantic dipole, we have noticed that, during cycles 19, 21, and 23, there were more positive phases, both with the occurrence of four phases each, the same was repeated for the negative phase, where these same cycles presented two negative phases each. When the Pearson correlation was used, between solar cycles and the teleconnections in question (ENSO, TSA, and TNA), the results have shown a low correlation and no significance. In this sense, further analysis was conducted, including only the ENSO and Atlantic Dipole phenomena, and their relationship with rainfall in the IGRC.

Teleconnections (ENSO and Atlantic Dipole) and the rains at the IGRC

To go deeper into the ENSO and Atlantic Dipole phenomena and their relationship with rainfall at the IGRC, we have decided to quantify only the years in which the data is complete, the period from 1950 to 2020, and separate Tables 4 to 8, according to the classification of years into rainfall classes (quantile order). Blue (and other shades of blue) represents higher rainfall values, La Niña events, and negative Dipole events. Red (light pink and orange) represents lower rainfall values, El Niño events, and positive Dipole. In Table 4, we show the years considered very rainy, by the quantile methodology, and one can see that, during the years in which rainfall was high, the TNA mostly remained in the negative status, being positive only in one year in the period from 1950 to 2020 (Table 4). As for ENSO, the pattern was random since the rains occurred in years with El Niño and La Niña. However, it is important to note that in the three rainy years with "moderate" El Niño, the phase of the negative Dipole occurred simultaneously.

Table 4. Teleconnections in very rainy years.

Very Rainy Years	Rainfall (mm)	ENSO	Dipole (phase)
1961	1052.2	Neutral	Positive
1963	1148.4	Moderate El Niño	
1964	1351.5	Moderate El Niño	
1972	979.7	Strong El Niño	Negative
1974	1560.5	Strong La Niña	Negative
1975	1162.6	Strong La Niña	Negative
1977	1144	Weak El Niño	
1985	1558.3	Moderate La Niña	
1986	1142.2	Moderate El Niño	Negative
1989	964.5	Strong La Niña	Negative
2002	991.2	Moderate El Niño	Negative
2009	1215.7	Moderate El Niño	Negative

Source: Elaborated by the authors.

As for the rainy years, when we talk about the phases of the Atlantic dipole, we have noticed that on seven occasions the phase was negative, and positive on only two. Therefore, this rainy period can be explained by this behavior of the anomaly in the tropical Atlantic temperature. The highest frequency of La Niña events associated with the rainy quartile was also observed (Table 5).

Table 5. Teleconnections in rainy years.

Rainy Years	Rainfall (mm)	ENSO	Dipole (phase)
1950	765	Strong La Niña	Negative
1960	794.8	Neutral	
1965	851.4	Strong El Niño	Negative
1967	792.6	Weak La Niña	
1968	832.2	Weak La Niña	
1971	964.1	Moderate La Niña	Negative
1978	838.1	Weak El Niño	Positive
1984	954.6	Weak La Niña	Negative
1994	847.2	Moderate El Niño	Negative
1996	846.6	Moderate La Niña	
2004	797.7	Weak El Niño	Positive
2006	760.8	Weak El Niño	
2008	875.2	Strong La Niña	Negative
2011	958.8	Strong La Niña	
2018	799.2	Moderate La Niña	Negative

Source: Elaborated by the authors.

In the table that corresponds to the years considered regular (Table 6), observing the phases of the dipole, it was noted that there is a predominance of the negative phase, with seven of them, and three positive ones. The El Niño event was predominant, compared to La Niña events, or periods of neutrality. There were six strong, four moderate, and four weak Niños in the period.

Table 6. Teleconnections in regular years.

Regular Years	Rainfall (mm)	ENSO	Dipole (phase)
1991	587.2	Strong El Niño	
1995	589.8	Moderate El Niño	Negative
2003	589.8	Moderate El Niño	
2013	597.6	Neutral	
2017	614.1	Weak La Niña	Negative
1976	617.3	Moderate La Niña	Positive
1959	627.5	Strong El Niño	Negative
1987	629.1	Strong El Niño	Negative
1982	648.3	Strong El Niño	Positive
1973	648.8	Moderate La Niña	Negative
1957	652.8	Strong El Niño	Negative
2000	657.1	Moderate La Niña	
1966	663.9	Moderate El Niño	
2014	671.2	Weak El Niño	
1969	695.4	Weak El Niño	
2016	698.7	Strong El Niño	Negative
1988	700	Strong El Niño	
2010	700.6	Moderate El Niño	Positive
1952	722.9	Weak El Niño	
2019	751.9	Neutral	

Source: Elaborated by the authors.

In Table 7, the dry years are shown. Regarding the Atlantic dipole gradient phases, we have observed a great predominance of the positive phase, which appeared in eight of the 14 dry years. There was also a predominance of El Niño events, whether weak, moderate, or strong.

Table 7. Teleconnections in years that are considered dry.

Dry Years	Rainfall (mm)	ENSO	Dipole (phase)
1954	409.7	Weak La Niña	Positive
1955	488.9	Moderate La Niña	
1956	531.3	Moderate La Niña	Positive
1962	407.7	Neutral	
1970	455.1	Moderate El Niño	Positive
1979	500.6	Weak El Niño	
1980	423	Moderate El Niño	
1981	519.9	Neutral	Positive
1990	441.8	Neutral	Positive
1992	486.1	Strong El Niño	
1997	399.9	Strong El Niño	Positive
2005	504.8	Weak El Niño	
2007	548.4	Weak El Niño	Positive
2015	399.6	Strong El Niño	Positive

Source: Elaborated by the authors.

In the previous table, concerning the Atlantic dipole, it is possible to see that the positive phase was predominant, appearing five times, against two of the negative phase. We can also see that there were six El Niño events and three La Niña ones (Table 8).

Finally, we have calculated the percentage of the appearance of teleconnections in each period (rainy, regular, and dry). We have found that in the "rainy and very rainy" periods, the negative phase of the Atlantic Dipole appeared in 52% of cases; followed by the neutral phase, with 37%; and the positive phase, with only 11%. We have also had 48% of occurrence of La Niña, 44% of El Niño, and 7% with the Pacific in the Neutral condition. In the "regular years", we have noticed that in 50% of the cases the neutral phase of the Atlantic Dipole predominated; followed by the negative one, with 35% of the cases; and the positive one with 15%.

The La Niña occurred in 20% of the years, El Niño in 70% and the Pacific was in the Neutral condition in 10% of them. When we observe the "dry and very dry years" the Atlantic Dipole positive phase predominates in 57% of the years; followed by the neutral phase, with 35%; and finally, the negative phase, with only 9%. We have found that La Niña occurred in 26% of the years, El Niño in 61%, and the neutrality of the Pacific in 13%.

Table 8. Teleconnections in years that are considered to be very dry.

Very Dry Years	Rainfall (mm)	ENSO	Dipole (phase)
1951	250.9	Moderate El Niño	Positive
1953	243.5	Weak El Niño	Positive
1958	170.2	Moderate El Niño	Positive
1983	300.1	Strong El Niño	
1993	153.9	Weak El Niño	Negative
1998	174.6	Strong El Niño	Positive
1999	308.7	Weak La Niña	
2001	371.8	Weak La Niña	Negative
2012	200.2	Moderate La Niña	Positive

Source: Elaborated by the authors.

When we selected the period from 1982 to 2020, the results were slightly different from those from 1950 to 2020, even so, there was a greater correlation between teleconnections, sunspots and rainfall.

The correlation matrix presents the values obtained for sunspots, Enso, Atlantic dipole, and rainfall, from 1982 to 2020. In detail, the ENSO was evaluated by region in the Pacific Ocean (Niño 1+2, Niño3, and Niño 3.4) and the Atlantic dipole by region in the Atlantic Ocean (TSA and TNA).

Table 9. Correlation analysis (correlation matrix) between teleconnections, sunspots and rainfall (annual values) for the period 1982 to 2020.

Correlation Matrix								
		EL NINO 12	EL NINO 3	EL NINO 34	TSA	TAN	Sunspots	rainfall mm/year
EL NINO 12	R de Pearson	—						
	Gl	—						
	p-value	—						
EL NINO 3	R de Pearson	0.845 ***	—					
	Gl	37	—					
	p-value	< .001	—					
EL NINO 34	R de Pearson	0.377 *	0.740 ***	—				
	Gl	37	37	—				
	p-value	0.018	< .001	—				
TAS	R de Pearson	-0.287	-0.324 *	-0.242	—			
	Gl	37	37	37	—			
	p-value	0.077	0.044	0.137	—			
TAN	R de Pearson	0.056	0.104	0.060	0.367 *	—		
	Gl	37	37	37	37	—		
	p-value	0.733	0.528	0.717	0.021	—		
Solar C	R de Pearson	0.010	0.016	-0.057	-0.431 **	-0.244	—	
	Gl	37	37	37	37	37	—	
	p-value	0.953	0.923	0.730	0.006	0.134	—	
TOTAL mm ano^{-1}	R de Pearson	-0.437 **	-0.394 *	-0.145	0.214	-0.317 *	-0.334 *	—
	Gl	37	37	37	37	37	37	—
	p-value	0.005	0.013	0.379	0.192	0.049	0.038	—

Nota. * p < .05, ** p < .01, *** p < .001; Source: Elaborated by the authors.

The result for the period from 1982 to 2020 was -0.4 for Rainfall and ENSO, Niño 1+2 with a 99% confidence level and Niño 3 with a 95% confidence level; and, for Rainfall and North Atlantic (TNA), it was -0.3, like rainfall and sunspots (-0.3), with a 95% confidence level, showing that there is a moderate correlation between rainfall in the IGRC and Sea Surface Temperature anomaly in the Pacific and a significant but weaker correlation between rainfall, Atlantic Surface Temperature anomaly and number of sunspots.

Discussion

Some mechanisms can explain the connection between solar activity and rainfall, and these mechanisms would imply opposite associations. A hypothesis for this relationship would be a type of cloud cover variation that would occur through the flow of cosmic rays, which, in turn, is modulated by solar activity through solar winds. Since the magnetic field carried by the solar wind partially protects the Earth from cosmic rays, when there is an increase in solar activity, there is consequently a decrease in their intensity (cosmic rays are inversely correlated with the parameters of solar activity). Parallel to this, there tends to be a decrease in cloud cover, as cosmic rays can induce an increase in it, through the production of condensation nuclei. This means that higher levels of solar activity denote a smaller flux of cosmic rays and would imply less cloud cover, and hence, less rainfall, assuming these clouds would culminate in rainfall (Svensmark & Friis-Christensen, 1997). The results presented here have shown a weak correlation between solar activity and rainfall, but also a weak and moderate correlation with the conditions of Atlantic Dipole and ENSO, indicating that the patterns of the Sun, Atlantic and Pacific oceans need to be carefully observed.

Since the presence of hot or cold events, called El Niño and La Niña, respectively, occur in the Tropical Pacific, positive or negative SST anomalies cause differentiated climatic impacts in several areas of the Brazilian Northeast, during El Niño periods, it is observed a decrease in rainfall and an increase in the years in which the La Niña occurs (Ferreira & Mello, 2005, Rodrigues, Haarsma, Campos, & Ambrizzi, 2011). Júnior and Sant'anna Neto (2015) bring, in their research, findings from several studies where ENSO is the main modulator of interannual variability, and the PDO has been considered an important mode of low and very low-frequency variability in decadal and multidecadal scales. According to Silva and Galvíncio (2011), during the occurrence of the positive phase of the PDO, there is a tendency for a greater number of El Niño events, and more intense and smaller numbers of La Niña ones, and less intense. During the negative phase of the PDO, there is a higher occurrence of La Niña events, which tend to be more intense, and a lower frequency of El Niño ones, which tend to be short and quick (Kayano & Andreoli, 2009). Thus, the negative phase of the PDO and La Niña events are favorable to rainfall in the Brazilian Northeast (Moraes Neto, Barbosa, and Araujo, 2007, Costa et al., 2020b).

Studies have also correlated anomalies in the temperature of the tropical Atlantic Ocean with rainfall in the Brazilian Semiarid Region, influencing the displacement of the Atlantic Intertropical Convergence Zone (ITCZ), which is the rainfall-producing system in the region (Utida et al., 2019). Uvo, Repelli, Zebiak, and Kushnir (1998), using climate data from 1946 to 1985, Kucharski, Polzin, and Hastenrath, (2008) using a climatological model from 1952 to 1992, Melo, Cavalcanti, and Souza (2009), analyzing a period from 1980 to 2004 and Utida et al. (2019), investigating changes in precipitation in the NEB using lacustrine sediments collected from Boqueirão Lake spanning the last 2,300 years (yrs), reached similar conclusions regarding the pattern of the Atlantic dipole and rainfall in the Brazilian semiarid region. Souza, Nogueira, and Nogueira (2017), analyzing the period from 1984 to 2015, observed a positive correlation between rainfall in the Brazilian semi-arid region and the South Atlantic Basin SST anomalies with 99% statistical significance. The authors identified that anomalously warm waters in the south tropical Atlantic and anomalously cold waters in the north tropical Atlantic (negative phase of the SST dipole) were related to the positive quality of the rainy season in the region. When the opposite pattern was observed, the quality of the rainy season was negatively affected.

Studies have also correlated El Niño and La Niña conditions associated with dry or rainy years in the Brazilian semiarid region, respectively (Marengo et al., 2018, Cunha et al., 2019, Medeiros & Oliveira, 2021). According to the research by Hastenrath (2006), the changes in the pressure field, promoted by El Niño conditions, intensify upper-tropospheric wave trains that extend from the eastern equatorial Pacific to the tropical Atlantic, weakening the Northeast trade winds and therefore bringing drier weather to the northern portion of the Brazilian Northeast (BNE). Cunha et al. (2019) also discuss that the El Niño has also been linked to the drought in some parts of Brazil, especially in the Northeast. Similarly, research by Marengo et al. (2018), showed that the drought conditions that began to intensify in 2012 were linked to an unusually warm tropical North Atlantic Ocean that favored an anomalous position north of the ITCZ and left less rainfall in the BNE. The conditions of the La Niña event in 2013 were not enough to offset the drought conditions established years earlier, and the El Niño in 2015 worsened these conditions thereafter. Studies with simulated anomaly values using NDVI agreed with the observed values for the period from 1951 to 1998, showing that the predicted NDVI anomalies coincided with historical ENSO-induced drought events in the Brazilian Northeast, as reported in the literature (Liu & Juárez, 2001). All the above-mentioned research used sea surface temperature data associated with atmospheric circulation patterns and rainfall. Regarding the delay of the atmospheric response (precipitation anomalies in the Brazilian semiarid region), associated with the warming or cooling of the Atlantic and tropical Pacific oceans, Wu et al. (2020) identified, for the period 1979 to 2018, that the time lags of the coupling of these oceans varied considerably from year to year. On average, lags of 2-3 months were identified from the oceanic regions (ENOS and Atlantic dipole). Similarly, the larger the sea surface temperature anomaly, the larger the lag for the atmospheric response. In that research, the coupling lags showed considerable episodic time scales, ranging from seasonal to interannual scales.

With the results found and those from the scientific literature, we have realized that studies on teleconnections and, mainly, extraterrestrial factors need to be further explored to try to understand the genesis of these teleconnection patterns, which are so important for rainfall forecasting in various parts of the globe, including the Brazilian semiarid region and the IGRC. Different temporal and spatial scales in the analysis could also bring interesting results for understanding rainfall variations, which are so common in the Brazilian semi-arid region. However, research on extra-atmospheric conditions should not be discarded in the genesis of rainfall variability on Earth and the Brazilian semiarid region, since the time series of rainfall data is short.

Conclusion

Through this research, it was possible to find important results regarding the pattern of rainfall at the Intermediate Geographic Region of Caicó (IGRC), in quantitative and qualitative terms, and its relationship with the ENSO and Atlantic teleconnections, as well as important data regarding the extra-atmospheric force exerted by the solar activity, through its cycles associated with the number of sunspots. From the data of the historical series, for the period 1913 to 2020, the Mann-Kendall test showed a positive trend for the rainfall variable, but with no statistical significance. The correlation between rainfall and sunspots for the entire historical series was equal to -0.2, indicating a weak correlation. However, after performing statistical tests, it was found that despite having a low r value, the null hypothesis was rejected, thus proving a statistical significance (0.05). In solar cycles 18, 19, 20, and 21, the correlation obtained was moderate, with the maximum value registered in cycle 21 (1976 to 1986), which was -0.7 (between moderate/strong), when there were periods of very heavy rains during the solar minimum and a period with below-average rainfall at the maximum of the cycle. This work has verified that only the variable related to solar activity, represented by the annual total of sunspots, is not sufficient to explain the pattern of rainfall in the studied area, so we have brought data from ENSO and Atlantic teleconnections to the analysis. Rainfall, when associated with the ENSO and Atlantic teleconnections, deserves attention since, in the "rainy and very rainy" periods, the negative phase of the Atlantic dipole appeared in 52% of the cases, and that of the occurrence of La Niña in 48% of them; and in the "dry and very dry" periods, the Atlantic positive phase predominated in 57% of the years, and El Niño predominated in 61% of them. The result of the correlation for Rainfall and ENSO (Niño 1+2 and Niño 3) was 0.4, and 0.3 for Rainfall and Atlantic Dipole (TNA), and 0.3 for rainfall and sunspots, with a 95% confidence level (1982 to 2020). Through the results found in this research and the literature on the subject, we can state that we should continue to include astronomical variables in climate studies as well as teleconnection patterns since this work has shown the complexity of the factors responsible for the high variability of precipitation in the study area (IGRC). It is suggested that this correlation analysis is applied to other areas of the Brazilian semiarid and of the country, since it is known that rainfall directly affects the surface of the planet, thus interfering in society and its activities.

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