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Seasonal Study on Changing Trends in Climatic Extremes Indicators in the Brazilian Territory

Estudo Sazonal sobre Mudança de Tendências em Indicadores de Extremos Climáticos no Território Brasileiro

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Abstract: This study focuses on analyzing trends in extreme climate indices in 11 different regions of Brazil on a quarterly basis, from 1961 to 2019. The aim is to identify changes in climate trends over time, particularly in terms of increasing climatic extremes, such as maximum and minimum temperature. Statistical tests were used to determine the presence of trends and the value of the changes. This study reveals that in most cities exhibited the minimum temperature recorded tends to increase in at least two quarters per year, while only a few did not show significantly increasing trends in maximum temperature. In terms of extreme temperature indices, a few regions presented statistically significant trends, such as Belém and Cuiabá, which showed a reduction in the occurrence of cold nights and hot days, respectively, across all quarters. Significant increases in the percentage of hot days and hot nights, as well as in maximum, minimum, and average temperatures across different regions, were observed. Additionally, in some seasons of the year precipitation events changed, with an increase in the concentration of rain in short periods and in the number of consecutive days without precipitation.
Keywords: climatic extremes; trend analysis; climatic timeseries.

Resumo: Este estudo analisa trimestralmente as tendências dos índices climáticos extremos em 11 diferentes regiões do Brasil, de 1961 a 2019. O objetivo é identificar as mudanças nas tendências climáticas ao longo do tempo, em termos de aumento nos extremos climáticos, como temperatura máxima e mínima. Testes estatísticos foram usados para determinar a presença de tendências significativas nas variações dos parâmetros climáticos e quantificá-las. Este estudo revela que a maioria das cidades apresentou uma tendência de aumento do valor da temperatura mínima registrada em pelo menos dois trimestres por ano, enquanto apenas algumas não apresentaram tendências de aumento significativo na temperatura máxima. Em relação aos índices de temperaturas extremas, apenas algumas regiões apresentaram tendências estatisticamente significativas, como Belém e Cuiabá, que apresentaram redução na ocorrência de noites frias e dias quentes, respectivamente, em todos os trimestres. Foi observado aumento significativo na porcentagem de dias e noites quentes, bem como nas temperaturas máximas, mínimas e médias em diferentes regiões. Adicionalmente, algumas estações do ano apresentaram mudanças nos eventos de precipitação, com aumento da concentração de chuvas em períodos curtos e do número de dias consecutivos sem precipitação.

Palavras Chave: Extremos climáticos; análise de tendências; séries temporais climáticas.

1 INTRODUCTION

The investigation of climate change has been a significant focus of research within scientific and academic circles in recent years. As the climate continues to evolve, the associated risks of climate extremes have become increasingly pertinent. Despite being rare occurrences, climate extremes are becoming more probable as global climate shifts. These changes, which are largely driven by climate change, have a substantial impact on the incidence of extreme events (EASTERLING et al., 2016). The urgency of understanding the magnitude and frequency of these events is paramount. Studies in some regions such as Belem-Pará, Curitiba, and the Belo Horizonte reveal the socioeconomic consequences and trends associated with these events. Extreme precipitation events in Belem-Pará resulting in significant impacts on neighborhoods like Cremação, Jurunas, and Batista Campos, underscoring the need for improved infrastructure Campos, Mota e Santos (2015). In Curitiba, a discernible trend towards intensified rainfall and increased extreme events underscores the complexity of climate change effects, with implications for urban planning and resilience Pedron et al. (2017). Similarly, the Metropolitan Region of Belo Horizonte reports a notable increase in daily precipitation events, emphasizing the importance of studying local climate indices and temperature changes to better prepare for potential impacts Nunes, Pinto e Baptista (2018). These investigations collectively underscore the critical role of understanding extreme events in adapting to changing climate patterns and enhancing resilience in vulnerable regions.

Extreme weather events refer to meteorological phenomena that deviate significantly from the long-term statistical norm of a particular climate region. These events are characterized by their exceptional intensity, duration, or frequency and can encompass a wide range of climatic phenomena, such as extreme heatwaves, severe storms, prolonged droughts, intense rainfall, and extreme cold spells. Extreme weather events are often defined based on statistical thresholds, such as events that exceed a certain percentile of the historical climatic distribution. They can have profound and often adverse impacts on ecosystems, infrastructure, human populations, and socioeconomic systems, making them a crucial focus of research in climate science and climate change studies. The most prominent indications of climate change, as they relate to extreme weather patterns, include reductions in the frequency of cold days and nights, an increase in the frequency of warm days and nights, and a surge in the occurrence of heavy precipitation events. Climatological research of the past is critical, as it allows us to comprehend the present and provides valuable insights for better understanding the behavior of climate patterns in the future.

The analysis of climate observations recorded at regular periods over time becomes essential when the objective is to predict or identify cycles and trends. Seasonal climate data analysis can provide valuable insights into climate trends and patterns, and several studies have demonstrated the usefulness of this approach. For example, Van Loon et al. (2014) used seasonal climate data to investigate how climate seasonality modifies drought duration and volume deficit. Their study found that the timing and duration of droughts can be affected by the seasonality of climate variables, such as temperature and precipitation. Kwiecien et al. (2022) conducted a transdisciplinary review of seasonality and concluded that it is a complex and multifaceted phenomenon requiring an integrated approach from different fields of study. These studies, along with others, highlight the importance of considering seasonal climate data analysis in climate research and decision-making.

Understanding the distribution and volume of precipitation throughout the year is crucial for the effective management of domestic and industrial water supply and power generation in countries dependent on hydroelectric power. Additionally, extremes and average values of temperature have a direct impact on the quality of life and economic activities, such as agricultural planning. Some activities may thrive in regions with lower temperatures, while others require higher temperatures for success.

Furthermore, studying climate quarterly can provide valuable insights that annual analyses may not capture. The quarterly analysis allows for a more detailed understanding of seasonal trends and the occurrence of extreme events. This approach can aid in developing targeted strategies to mitigate the impacts of climate change on local populations and industries. As demonstrated in the study conducted by Machado et al. (2021), the analysis of extreme rainfall indices in the macrometropolis of São Paulo (MMSP) revealed intriguing patterns. The research, identified three distinct homogeneous regions within MMSP based on the annual cycle of rainfall. Notably, the entire MMSP exhibited an average annual increase in total rainfall, as verified through the

Mann–Kendall test. It is noteworthy that these correlations are not uniform throughout the year, particularly during the dry season. Importantly, the research underscores that rainy anomalous months are more frequent and closely associated with climatic indices, compared to the occurrence of dry months.

The primary objective of analyzing time series data is to detect non-random patterns in the variables of interest. In the case of climate series, these analyses are particularly useful for identifying relevant trends, especially with respect to extreme climate indicators, such as the number of days with maximum or minimum temperatures, consecutive dry days, or rainfall concentration during shorter periods.

There are various methodologies and techniques for identifying climate trends, especially in relation to precipitation and temperature. A range of statistical methods can be employed to detect positive or negative trends in time series data. In the context of climate series, the Mann-Kendall test (Mann (1945) and Kendall (1975)) and Sen's slope (Sen (1968)) are commonly utilized.

The World Meteorological Organization (WMO) charged the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) to develop a standardized set of climate indicators for regional comparisons and identifying potential climate change. This expert team has identified 27 key climate indicators based on daily measurements, including 16 temperature indicators and 11 precipitation indicators. This indicator model has gained widespread acceptance due to its ability to capture extreme events, having a greater impact on measuring climate change than traditional indicators. Previous studies (NÓBREGA; LIMA FARIAS; SANTOS, 2015; NATIVIDADE; GARCIA; TORRES, 2017) have identified past, current, and future climate trends.

The present study proposes a methodology for detecting significant trends in climate extremes, with a specific focus on temperature and rainfall, on a quarterly basis. The indicators used to measure these trends include the number of hot and cold days, maximum and minimum temperatures, and average temperatures. Additionally, the study examines the number of consecutive days with and without rainfall, maximum daily rainfall, and precipitation levels. Changes in these indicators have a significant impact on the population, including water consumption and electricity generation from hydroelectric plants during periods of drought, as well as changes in energy consumption habits and impacts on agriculture caused by increased temperatures or more hot days in a year. This study shows that temperatures have increased throughout the year in all quarters, for all cities, with some regions experiencing trends for dry periods, and others showing an increase in the volume of rainfall over a shorter period. These trends highlight the need for adaptation measures to mitigate the impacts of climate change, such as the development of water management plans and the use of drought-resistant crops in affected regions.

This paper represents an expanded edition of the research conducted by Coelho et al. (2021), initially presented during the XXII Brazilian Symposium on GeoInformatics (GEOINFO 2021), with the main objective to observe whether the trends identified annually are more prominent in a given period of the year. A quarterly analysis was additionally implemented to see the distribution of these trends throughout the year. In this paper, we calculate and analyze these indicators for 11 Brazilian cities, each with a different climate configuration, to identify whether trends are changing throughout the Brazilian territory. Results are analyzed using confidence intervals compatible with other works in the literature. A seasonal analysis approach was implemented on the databases to further explore the observed trends to determine if the previously identified annual trends were consistent throughout all quarters of the year or if they were more pronounced during specific periods.

The remainder of this text is organized as follows. Section 2 presents a literature review. Section 3 describes data acquisition and preprocessing analysis. Section 4 describes trend analysis methods. Section 5 presents the experiments and the results obtained. Section 6 presents the discussion of results. Section 7 presents our conclusions.

2 Related Work

Numerous climate change detection methods have been proposed in the literature for specific regions. This article seeks to identify and implement the most effective time series analysis techniques to detect changes in extreme indices in various regions of Brazil.

The use of statistical analysis on time series data is a common approach in climate change research. A study by Santos e Nishiyama (2016) aimed to investigate the correlation between land use and occupation dynamics in the upper Uberaba (MG) basin over the past three decades, identified significant trends of decreasing annual rainfall totals and rainfall during the dry period using various statistical tests. Similarly, Penereiro e Orlando (2013) detected changes in hydrological and climatic behavior in the Parnaiba river basin in Northeastern Brazil. However, due to the complexity of establishing links between changes observed in time series data and the natural and anthropogenic effects on climate, the analysis recommends caution in interpreting the possible causes of these changes. Nevertheless, the findings confirm the existence of trends in the maximum, minimum, and average temperature series, as well as annual precipitation.

In their research using data from Viçosa (MG), Avila-Diaz et al. (2020) assessed trend analysis methodologies in extreme climate indices. Their findings revealed significant upward trends at a 5% significance level for extreme annual temperatures, in addition to increased frequency of torrential rains during the summer and decreased frequency during the winter. Similarly, Alencar et al. (2014) investigated various climate indicators in Catalao (GO) through the application of non-parametric tests, including Mann-Kendall and Sen's Slope. Their analysis indicated an evolution in maximum and minimum temperatures, with a statistically significant increase observed in both extreme temperature indices, along with a decline in relative humidity, and notable increases in reference evapotranspiration for various months throughout the year and the annual series.

In line with Dalagnol et al. (2022), our research seeks to understand variations in extreme climate indices and their potential effects in various climatic regions of Brazil. By analyzing total precipitation and precipitation on extremely wet days (PRCPTOT and R95P, respectively), the Dalagnol et al. (2022) study linked an extreme event to human-induced climate change and revealed its devastating socio-economic impacts. Our study seeks to provide valuable information for the elaboration of policies for mitigation and adaptation to climate change, with the aim of preventing future disasters and their associated socioeconomic costs.

The study conducted by Regoto et al. (2021) provides an analysis of seasonal and annual trends of extreme indices of air temperature and precipitation over Brazil during the period 1961-2018, revealing a very consistent and widespread warming over Brazil. The frequency of occurrence of warm extremes is increasing significantly, while the opposite occurs for cold extremes.

Kessabi et al. (2022) investigated trends in seasonal rainfall in the Mediterranean region, specifically in the Sebou watershed in northern Morocco. Using nonparametric tests, the authors analyzed 15 monthly rainfall series across the basin and discovered a significant decrease in winter and spring rainfall, with a range of -7 mm to -47 mm per decade in winter months and an average of -12 mm per decade in spring. These findings have critical implications for the Sebou watershed, which is already experiencing significant water stress and heavily relies on rain-fed agriculture.

3 Data Acquisition and Analysis

The National Institute of Meteorology (INMET) manages more than 400 meteorological stations, conventional and automatic, spread throughout the Brazilian territory. In this study, were used daily data from 11 different meteorological stations with their geographic locations (Figure 1). These cities were chosen because they represent the different climatic regions of the Brazilian territory. Also, datasets on the selected cities are more extensive and with less missing values.

Common Climate Characteristics:

- **Hot:** Regions with consistently high temperatures.
- **Sub-Hot:** Areas with relatively high temperatures but moderated compared to hot climates.
- **Semi-Arid:** These regions experience limited precipitation, resulting in arid conditions.
- **Semi-Wet:** Areas with moderate rainfall but not classified as consistently wet.
- **Mild Mesothermic:** Regions characterized by mild temperatures throughout the year.

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- **Superwet:** Areas receiving a substantial amount of rainfall, often exceeding the average.

Specific Climate Characteristics:

- **Sub-Hot Semi-Moist (City #4):** Moderately high temperatures with a semi-moist environment, typically having four to five dry months during the year. A balance between heat and moisture.
- **Semi-Arid Hot with 6-8 Dry Months (City #2):** High temperatures and a prolonged dry season lasting 6 to 8 months. Precipitation is limited, leading to arid conditions.
- **Hot Wet (City #3):** Consistently high temperatures and abundant rainfall throughout the year. A hot and humid environment.
- **Semi-Arid Hot with 9-11 Dry Months (City #5):** Intense heat and an extended dry season, lasting 9 to 11 months. Precipitation is scarce, contributing to arid conditions.
- **Mild Mesothermic Wet (City #6):** Mild temperatures year-round with ample rainfall providing a wet environment.
- **Hot Semi-Moist (City #7):** Consistently high temperatures and a moderate amount of rainfall, sustaining a warm and somewhat humid climate.
- **Mild Mesothermic Superwet (City #8):** Mild temperatures and significant rainfall, often exceeding average levels. A superwet climate with abundant precipitation.
- **Hot Superwet (City #9):** Consistently high temperatures and heavy rainfall year-round, contributing to a hot and very humid environment.
- **Sub-Hot Wet (City #10):** Moderately high temperatures and a notable amount of rainfall, creating a balanced climate with wet conditions.
- **Sub-Hot Superwet (City #11):** Sub-hot temperatures and an abundance of rainfall, particularly during the wet season. A superwet environment.

Figure 1 – Selected stations and their respective locations

City/State	Climate region
(1) Araxá/MG	Semi-wet mild mesothermic
(2) Barbalha/CE	Semi-arid hot 6-8 dry months
(3) Belém/PA	Hot wet
(4) Belo Horizonte/MG	Sub-hot semi-moist with 4 to 5 dry months
(5) Cabrobó/PE	Semi-arid hot 9-11 dry months
(6) Caparaó/MG	Mild mesothermic wet
(7) Cuiabá/MT	Hot semi-moist
(8) Curitiba/PR	Mild mesothermic superwet
(9) Manaus/AM	Hot superwet
(10) São Simão/SP	Sub-hot wet
(11) São Paulo/SP	Sub-hot superwet

Source: Coelho et al. (2021)

To perform the calculation of indicators of climatic extremes, the study uses parameters from the Meteorological Database of INMET (BDMEP)[1], collected from automatic and conventional stations. The

[1] https://bdmep.inmet.gov.br/

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parameters are date, daily minimum temperature, daily maximum temperature and total daily precipitation. All extreme indicators used in this work were calculated according to the definitions established by ETCCDMI Climate Change Indices.

To estimate the missing volume of data, the amount of days that each database should have, according to the initial and final year of the temporal series, and compared to the total number of lines (days) existed in the database. The percentage of missing data in each temporal series can be seen in the Table 1.

Table 1 – Percentage of missing data for each staion analysed

City	**Percentage of missing data**
Araxá	9.70%
Barbalha	6.29%
Belém	5.06%
Belo Horizonte	5.05%
Cabrobó	17.13%
Caparaó	30.58%
Cuiabá	7.95%
Curitiba	2.46%
Manaus	3.75%
São Paulo	3.20%
São Simão	15.14%

Source: The authors (2023).

Table 2 contains the definition of the extreme temperature indicators we calculated and used in this work.

Table 2 – Extreme temperature indicators recommended by ETCCDMI

TXx	Hottest day	Highest daily maximum temperature value	°C
TX10P	Cold days	Percentage of days with minimum daily temperature <10th percentile of the period	% of days
TX90P	Hot days	Percentage of days with maximum daily temperature >90th percentile of the period	% of days
TNn	Coldest night	Lowest daily minimum temperature value	°C
TN10P	Cold nights	Percentage of days with minimum daily temperature <10th percentile of the period	% of days
TN90P	Hot nights	Percentage of days with minimum daily temperature >90th percentile of the period	% of days

Source: Coelho et al. (2021).

Table 3 contains the definition of extreme rainfall indicators calculated and used in this work. Both set of extreme indices were obtained from ETCCDMI site[2].

[2] http://etccdi.pacificclimate.org/list_27_indices.shtml

Table 3 – Extreme rainfall indicators recommended by ETCCDMI

PRCPTOT	Total precipitation per period	Total period precipitation on wet days with daily precipitation rate >1mm	mm
R95P	Very rainy days	Total period precipitation when the daily precipitation rate >95th percentile of precipitation for the selected period	mm
RX1DAY	Maximum precipitation in 1 day	Highest volume of rain recorded in 1 day	mm
RX5DAY	Maximum precipitation in 5 days	Highest volume of rain recorded in 5 consecutive days	mm
CDD	Consecutive dry days	Maximum number of consecutive dry days with daily precipitation rate >1mm	days
CWD	Consecutive wet days	Maximum number of consecutive wet days with daily precipitation rate <1mm	days

Source: Coelho et al. (2021).

In addition to the aforementioned indices, the mean annual and quarterly temperature (Tavg) was calculated for all cities.

In this study, the authors used the timeseries of daily climate data obtained from the BDMEP database to generate subseries for each respective index of interest. For instance, a new time series was created for TXx (Table 2) by selecting the maximum temperature recorded for each period, year and quarter, in the main time series. Similarly, a new series was generated for RX5day (Table 3) by identifying the largest amount of precipitation recorded in 5 days of each period of the main time series.

To obtain a more comprehensive understanding of seasonal climate variations, the data was grouped into quarters and analyzed as was done in annual approach. This approach facilitated a better examination of temperature, precipitation and the climatic extremes indicators throughout the year. By analyzing the data quarterly, the authors were able to remove short-term fluctuations such as random weather events and noise in the data, enabling them to uncover longer-term trends and patterns. Additionally, using quarterly data aligned with the reporting cycles of many organizations, making it easier to communicate and share the data with others. The use of quarterly data allowed for easier comparisons of climate data across different years or regions, providing valuable insights into how climate is evolving over time.

Subsequently, the climate indicators were subjected to trend tests using the nonparametric Mann-Kendall test (MANN, 1945; KENDALL, 1975), and the magnitude of these trends was determined using Sen's Slope estimator (SEN, 1968). A similar analysis was conducted for average temperature data and, warming stripes visualizations were created to facilitate comparison of temperature fluctuations across the quarters and years.

All indices for the annual approach were calculated using the computational package RClimdex (ZHANG; YANG, 2004), and for the seasonal approach the authors created a script using python to calculate the indices quarterly.

4 Methods of trend analysis

The main objective of trend analysis is to identify the existence of significant trends of increasing or decreasing in a data series. Tests for detecting these trends can be classified as parametric and non-parametric methods. The parametric tests require the data to be independent and normally distributed, while non-parametric tests only require the data to be independent Mirabbasi, Ahmadi e Jhajharia (2020). For this study, the non-parametric Mann-Kendall and Sen's Slope tests were used.

The tests applied to this study can be replicated from the instructions provided in our repository **https://gitlab.com/filipesantos.lf/study-on-changing-trends.git**.

4.1 Mann-Kendall Test

The Mann-Kendall test (MANN, 1945; KENDALL, 1975) is a robust, sequential, non-parametric method used to determine whether a given data series has a statistically significant tendency to change its pattern of data behavior over time. As it is a non-parametric method, it does not require normal data distribution (YUE; PILON; CAVADIAS, 2002). Another advantage of this method is that it is little influenced by abrupt changes or non-homogeneous series (ZHANG et al., 2009; NEETI; EASTMAN, 2011).

The method is based on the rejection or not of the null hypothesis (H_0), that states there is no trend in the data series, adopting a significance level (α). The significance level can be interpreted as the probability of making the error of rejecting H_0 when it is true. The statistical variable S, for a series of n data from the Mann-Kendall test, is calculated from the sum of the signs (sgn) of the difference between pairs of all values in the series (x_i) in relation to their future values (x_j) (Equations 1 and 2). When $n = 10$, the variable S can be compared with a normal distribution, in which the variance, $Var(S)$, can be obtained from Eq. 3, in which t_i represents the number of repetitions of an extension i.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

$$sgn(x_j - x_i) = \begin{cases} +1 & \text{if} \quad x_j > x_i \\ 0 & \text{if} \quad x_j = x_i \\ -1 & \text{if} \quad x_j < x_i \end{cases} \tag{2}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(i)(i-1)(2i+5)}{18} \tag{3}$$

For example, a historical series with three values equal to each other would have 1 repetition of extension equal to 3, or $t_i = 1$ and $i = 3$.

The index Z_{MK}, generated by the Mann-Kendall test, follows the normal distribution, in which the mean is equal to zero. Positive values indicate an increasing trend, and negative ones indicate a decreasing trend. According to the sign of S, the index Z_{MK} of the normal distribution is calculated from:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{for} \quad S > 0, \\ 0 & \text{for} \quad S = 0, \\ \frac{S+1}{\sqrt{Var(S)}} & \text{for} \quad S < 0. \end{cases} \tag{4}$$

As it is a two-tailed test, the absolute value of Z_{MK} to reject H_0 must be greater than $Z_{\alpha/2}$. For example, for $\alpha = 0.05$, $Z_{0.05/2} = Z_{0.025} = 1.96$, with the value obtained from the table of the standard normal distribution. Therefore, the series will be considered to have a significant trend at the 0.05 level if $|Z_{MK}| > 1.96$, 0.10 level if $|Z_{MK}| > 1.65$ and 0.15 level if $|Z_{MK}| > 1.44$.

In this article, the Mann-Kendall test was used to identify trends of increasing or decreasing values in extreme weather indices. It was also applied to the Tavg indicator to verify the existence of a trend of change in the average annual temperature.

4.2 Sen's slope estimator

Despite the efficiency of the Mann-Kendall test, it does not provide the magnitude of the trends detected and can be complemented by the slope estimator proposed by Sen (1968). This method is insensitive to outliers and missing data, being more rigorous than linear regression curvature, providing a more realistic measure of trends in time series. As described by Portela et al. (2011), it is necessary first to estimate the Q statistic, given by:

$$Q_{ij} = \frac{X_j - X_i}{j - i} \quad \text{for} \quad i < j \tag{5}$$

where X_i and X_j represent the values of the variable under study in the years i and j. Positive or negative value for Q indicates increasing or decreasing trend, respectively. If there are n values in the analyzed series, then the number of estimated pairs of Q is given by $N = n(n-1)/2$. Sen's slope estimator is the median of the N values of Q_{ij}.

Using the BDMEP dataset, the extreme indices described in Table 2 and Table 3 were calculated at annual and quarterly intervals for each of the cities selected to represent the different climate regions defined by IBGE. With the database complete and aiming at detecting significant trends with the proper quantification, the non-parametric Mann-Kendall test, complemented by the Sen's slope estimator that identifies the amplitude of the trends, was applied to the time series of the 13 chosen indices.

5 Results

5.1 Quarterly analysis

Table 4 and Table 5 present the range of significant trends considered at a 95% confidence level for the purpose of presenting the results in a simplified manner.

5.1.1 RAINFALL ANALYSIS

Upon closer examination of the quarterly approach, it becomes apparent that not all observed trends of increase in annual precipitation manifest across all quarters as seen in Table 4. Notably, the Hot Wet region displays such a trend across quarters 1, 2, and 4, while all quarters exhibit a positive trend for R95P. Curitiba, representing the Mild mesothermic superwet region, reveals an upward trend for the fourth quarter, leading to the hypothesis that the observed annual increase may be concentrated towards the end of the year.

Table 4 – Results for tests applied to quarter rainfall indicators.

City	Quarter	CDD	CWD	PRCPTOT	R95p	RX1DAY	RX5DAY
Barbalha	1	0.07692	-	-	-	-	-
	3	0.71241	-	-0.30000	-0.26377	-0.13391	-0.29018
	4	0.25000	-	-	-	-	-
Belo Horizonte	2	-	-	0.93333	-	-	-
	4	0.08333	-	-	-	-	-
Belém	1	-	-	7.12286	1.00526	-	1.00526
	2	-	-	6.23421	1.91569	-	1.91364
	3	-	-	-	0.63125	-	-
	4	-	-	3.59667	1.14286	0.27273	1.14286
Caparaó	1	0.15789	-	-	3.25000	0.54545	1.95000
	2	-	-	-	1.61000	-	1.52817
Cuiabá	1	-	-0.07692	-	-	-	-
	4	-	-0.04000	-	-	-	-
Curitiba	1	-	-	-	0.80659	-	0.80000
	2	0.04762	-0.03704	-	-	-	-
Manaus	1	-	-0.08333	-	-	-	-
	4	-	-	2.77133	1.63006	0.48918	1.51844
São Paulo	1	-	-	3.62778	0.98710	-	1.04167
	3	0.15625	-	-	-	-	-
	4	-	-	-	-	0.30606	-

Source: The authors (2023).

Unlike the annual analysis, the quarterly approach highlights a trend towards increased rainfall volume in the second quarter of the sub-hot semi-moist region with 4 to 5 dry months.

The region characterized as Semi-arid hot 6-8 dry months displays significant negative trends for all volume of precipitation indicators in its third quarter, including PRCPTOT, R95P, RX1DAY, and RX5DAY. Linked to this observed reduction in the volume of rainfall, an increase trend in the CDD is observed, demonstrating real trends of a dry period for the region. The positive CDD is also present in the first and fourth quarters. This results can be compared with the annual. These results are very similar to those obtained in the annual analysis, demonstrating where they are concentrated throughout the year.

5.1.2 TEMPERATURE ANALYSIS

It is worth noting that all cities analyzed in this study show a warming trend in average temperature, with the exception of the second and third quarters in the city of São Simão (Table 6). This trend is particularly notable in the first and third quarters in Caparaó (Table 6), which is classified as a Mild mesothermic wet region, with an amplitude of 0.07101 ºC/decade. Overall, the analysis indicates a clear warming trend across all cities and quarters studied observed in Table 5 and Table 6.

Table 5 – Results for tests applied to quarter temperature indicators.

City	Quarter	TXx	TX10p	TX90p	TNn	TN10p	TN90p	Tavg
Araxá	1	0.0333	-	-	0.0519	-	-	0.0407
	2	0.0556	-	-	0.0714	-0.0039	-	0.0439
	3	0.0800	-	-	0.0667	-	-	0.0587
	4	0.0742	-	-	0.0321	-	-	0.0512
Barbalha	1	0.0690	-	-	-	-	-	0.0328
	2	0.0677	-	-	-	-	-	0.0332
	3	0.0631	-	-	0.0333	-	-	0.0249
	4	0.0500	-	-	0.0541	-0.0133	-	0.0308
Belo Horizonte	1	0.0255	-	-	0.0326	-	-	0.0264
	2	-	-	-	0.0625	-	-	0.0247
	3	0.0400	-	-	0.0481	-	-	0.0289
	4	0.0500	-	-	0.0276	-	-	0.0328
Belém	1	0.0194	-	-	0.0222	0.0235	-	0.0230
	2	0.0222	-	0.0175	0.0222	0.0285	-	0.0240
	3	0.0353	0.0234	0.0226	0.0276	0.0401	-	0.0338
	4	0.0333	-	-	0.0364	-	0.0329	0.0317
Cabrobó	1	0.0214	-0.0197	-	0.0250	-	-	0.0373
	2	0.0458	-	-	0.0480	-	-	0.0461
	3	0.0603	-	-	0.0313	-	-	0.0240
	4	0.0321	-	-	0.0261	-	-	0.0264

Source: The authors (2023).

Among all the cities analyzed, only a few did not show statistically significant increasing trends in maximum temperature at a confidence level of 0.05. These include Belo Horizonte in the second quarter, Caparaó in the second and fourth quarters, and Cuiabá in the first and second quarters. Notably, Caparaó exhibited a significant increase in maximum temperature during the third quarter with an amplitude of approximately 0.1ºC/decade.

Except for São Simão, all cities exhibited a tendency to increase the value of the minimum temperature recorded in a minimum of two quarters per year.

In contrast to the annual analysis, only a few regions exhibited statistically significant trends in the extreme temperature indices that represent hot and cold days and nights. Notably, the city of Belém showed a negative trend for the TX10P index, indicating a reduction in the occurrence of cold nights from the first to the third quarter. Similarly, the city of Cuiabá exhibited a decrease in the occurrence of hot days (TX10P) across all quarters.

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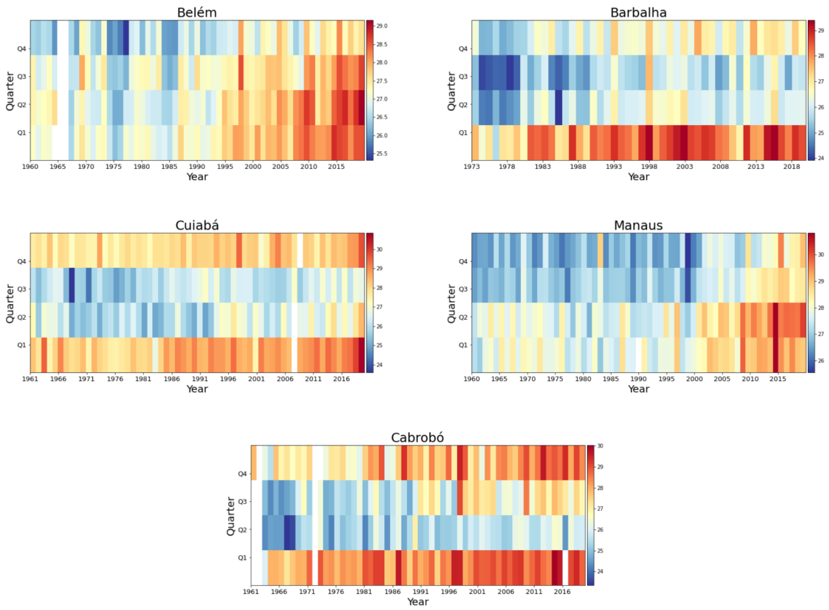
Table 6 – Results for tests applied to quarter temperature indicators.

City	Quarter	TXx	TX10p	TX90p	TNn	TN10p	TN90p	Tavg
Caparaó	1	0.0500	-	-	0.0676	-	-0.0397	0.0603
	2	-	-0.0157	-	0.1000	-0.0095	-0.0353	0.0442
	3	0.0941	-	-	-	-	-	0.0374
	4	-	-	-	-	-	-	0.0710
Cuiabá	1	-	0.0055	-	0.0348	-	-	0.0165
	2	-	0.0021	0.0118	-	0.0046	-	0.0159
	3	0.0422	-0.0012	-0.0185	0.0333	-	-0.0148	0.0235
	4	0.0261	-0.0059	-	0.0476	-	-	0.0244
Curitiba	1	0.0259	-	-	0.0443	-	-	0.0271
	2	0.0266	-	-	0.0767	-	-	0.0359
	3	0.0366	-	-	0.0500	-	-	0.0322
	4	0.0304	-	-	0.0852	-	-	0.0330
Manaus	1	0.0217	-	-	0.0125	-	-	0.0270
	2	0.0250	-	-	0.0250	-	-	0.0273
	3	0.0330	-	-	0.0333	-	-	0.0332
	4	0.0209	-	-0.0011	0.0146	-	-	0.0270
São Paulo	1	0.0435	-	-	0.0500	-	-	0.0316
	2	0.0323	-	-	0.0647	-	-	0.0335
	3	0.0391	-	-	0.0681	-	-	0.0327
	4	0.0533	-	-	0.0500	-	-	0.0457
São Simão	0	0.0429	-	-0.0060	-	-	-	0.0150
	0	0.0333	-	-	-	-	-	-
	0	0.0656	-	-	-	-	-	-
	0	0.0768	-	-	-	-	-	0.0354

Source: The authors (2023).

Figure 2 shows warming stripes for cities with hot climates that present an average temperature above 18°C every month of the year. We can observe that for the city of Barbalha, the increase in average temperature is more accentuated in the first quarter and more subtle in the others. Belém and Manaus are the cities that best describe the warming indicated in the trends observed throughout the year.

Figure 2 – Quarterly warming stripes hot region



Source: The authors (2023).

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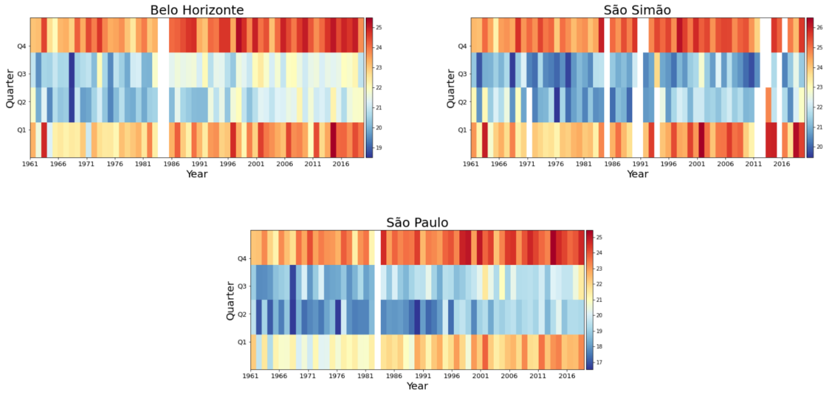
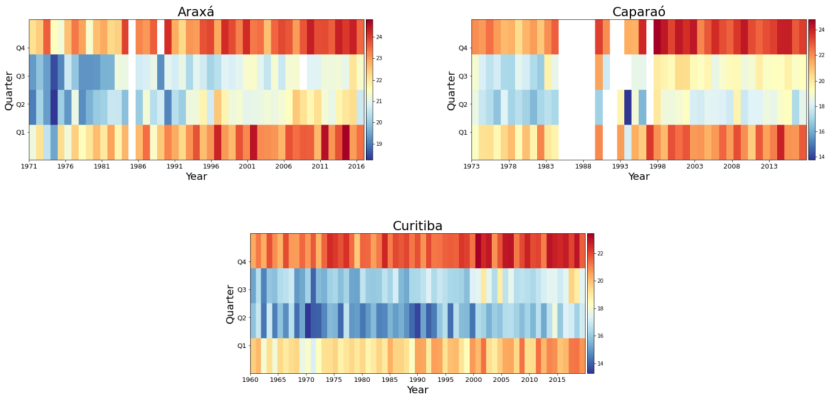
Figure 3 – Quarter warming stripes sub-hot region



Source: The authors (2023).

The average temperature of the sub-hot region was shown Figure 3, which, according to IBGE, presents an average temperature between 15ºC and 18ºC in at least 1 month. The city of Belo Horizonte presents a better distribution of warming over the quarters, unlike São Paulo and São Simão, which present more subtle variations for the intermediate quarters.

Figure 4 – Quarter warming stripes mild mesothermal region



Source: The authors (2023).

The temperature graphs presented in Figure 4 depict the average temperature of the mild mesothermal region, which is characterized by an average temperature ranging from 10°C to 15°C according to IBGE. The results observed in this region are similar to those of the other regions mentioned earlier, with temperature increases greater than 17°C for the intermediate quarters. However, for the first and last quarter, the temperature ranges from 23ºC to 24ºC.

6 Discussion

Table 7 and Table 8 summarize the results obtained, placing side by side the values obtained in this study and the results obtained in Coelho et al. (2021). This research provides new perspectives on temperature and precipitation extreme trends in various Brazilian cities. In terms of temperature, all 11 cities examined displayed rising trends in quarterly maximum (TXX), minimum (TNn), and average (Tavg) temperatures with 95% confidence. Moreover, the decrease in the number of cold days (TX10p and TN10p) and the increase in the number of hot days (TX90p and TN90p) was not observed in all quarters. Regarding precipitation, trends were more diverse. For precipitation indicators, such as consecutive dry days (CDD), consecutive wet days (CWD), maximum 1-day precipitation (RX1DAY), maximum 5-day precipitation (RX5DAY), very wet days (R95P), and total precipitation (PRCPTOT), the differences between the annual and quarterly analyses were more noticeable. Although some cities like Belem, Cuiaba, Manaus, and Sao Paulo showed an increase in total precipitation on both annual and quarterly scales, patterns varied significantly across seasons. In summary, findings indicate consistent warming across Brazil, with rising annual maximum, minimum, and average temperatures, as well as increased frequency of hot days and reduced cold days. Precipitation trends, however, are more varied, with some regions showing increased total rainfall volume and heavy rain events, while others reveal changes in rainfall distribution over the year. These regional differences can be attributed to Brazil's climatic and geographical variations, which encompass a wide range of ecosystems and weather conditions.

Table 7 – Summary and comparison of the temperature results of the approaches.

Indicators	Annual Results	Quarterly Results
TXx	8 cities had a increase trend, except: Belém/PA, Caparaó/MG and São Simão/SP	All cities had a trend in almost every quarter, except: Quarter 2 from Belo Horizonte/MG, Caparaó/MG and Cuiabá/MT
TX10P	9 cities had a falling trend, except: Belo Horizonte/MG, Caparaó/MG	Falling trends: Quarter 1 of Cabrobró/PE Quarter 2 from Caparaó/MG Quarter 3 and 4 from Cuiabá/MT Increase trends: Quarter 3 from Belém/PA Quarter 1 and 2 from Cuiabá/MT
TX90P	All cities11 had a increase trend	Falling trends: Quarter 3 from Cuiabá Quarter 1 from São Simão/SP Quarter 4 from Manaus Increase trends: Quarter 2 and 3 of Belém Quarter 2 from Cuiabá
TNn	10 cities had a increase trend, except: São Simon	10 cities showed an increase in almost every quarter, except: Quarters 1 and 2 of Barbalha/CE Quarters 3 and 4 of Caparaó/MG Quarter 2 from Cuiabá/MT Quarter 1, 2, 3 and 4 of São Simon did not present any period
TN10P	10 cities had a falling trend, except: Barbalha/CE	Falling trends: Quarter 2 of Araxá and Caparaó Quarter 4 from Barbalha Increase trends: Quarters 1, 2 and 3 Belo Quarter 2 from Cuiabá
TN90P	10 cities had a increase trend, except: Barbalha/CE	Falling trends: Quarters 1 and 2 of Caparaó Quarter 3 from Cuiabá Increase trends: Quarter 4 from Belém
Tavg	All cities 11 had a increase trend	Cities have obtained high trend in almost every quarter Only Quarters 2 and 3 of São Simon did not reach 95% confidence

Source: The authors (2023).

These findings are in line with earlier investigations into climate change and extreme climatic conditions in Brazil, including the study by Regoto et al. (2021), which also identified an increasing frequency of warm extremes and a decreasing frequency of cold extremes, suggesting consistent and widespread warming throughout Brazil. Regoto et al. (2021)'s analysis also exposes shifts in precipitation trends, with diverse signals in different areas of the country. Northeastern Brazil is experiencing a transition towards a drier climate, while the southern region is becoming more humid. These tendencies are also in line with our findings, which demonstrate an increase in annual precipitation in the hot region and a negative precipitation trend in the semi-arid hot region with 6-8 dry months. When comparing our results with the study by Marengo et al. (2009), it is evident that the increasing trends in maximum and minimum temperatures, as well as the frequency of extreme heat events, are consistent with their findings. However, our research broadens the analysis by incorporating various precipitation indicators, emphasizing the diverse precipitation trends in distinct regions of Brazil. Climate change can influence extreme precipitation events, as shown in the study by Dalagnol et al. (2022) on excessive rainfall in Minas Gerais state in January 2020. This examination connects extreme precipitation events to climate change and implies that such occurrences may become more frequent or intense in the future. In our research, we observe an increase in annual precipitation, particularly in very heavy rainfall events (R95P) and total annual precipitation (PRCPTOT) for the hot climate and its subclimates. The quarterly analysis emphasizes the heterogeneous distribution of precipitation throughout the year, with some regions exhibiting positive trends and others, negative trends.

Table 8 – Summary and comparison of the rainfall results of the approaches.

Indicators	Annual Results	Resultados RBC
CDD	1 city with increase trend (Barbalha/CE) and 95% trust	Increase trends: Quarter 1: 2 cities (Barbalha/CE and Caparaó/MG) Quarter 2: 1 City (Curitiba/PR) Quarter 3: 2 cities (Sao Paulo/SP and Barbalha/CE) Quarter 4: 2 cities (Belo Horizonte/MG and Barbalha/CE)
CWD	1 City (Barbalha/CE) with falling trend	Falling trends: Quarter1: 2 cities (Cuiabá/MT and Manaus/AM) Quarter 2: 1 City (Manaus/AM) Quarter 4: 1 Cycidade (Cuiabá/MT)
RX1DAY	3 cities with an increase trend (Curitiba, Manaus and São Paulo) above 95%	Falling trends: Quarter 3: 1 City (Barbalha/CE) Increase trends: Quarter 4: 3 cities (Belém/PA, Manaus/AM, São Paulo/SP) Quarter 1: 1 City (Caparaó/MG)
RX5DAY	2 cities with an increase trend (Belém/PA and Manaus/AM above 95%)	Falling trends: Quarter 3: 1 City (Barbalha/CE) Increase trends: Quarter 1: 4 cities (São Paulo/SP, Curitiba/PR, Caparaó/MG, Belém) Quarter 2: 2 cities (Belém/PA, Caparaó/MG) Quarter 4: 2 cities (Manaus/AM, Belém/PA)
R95P	4 cities with a trend of increase above 95% (Belém/PA, Cuiabá/MT, Manaus/AM, São Paulo/SP) 1 city with a falling trend over 95% (Cabrobó/PE)	Falling trends: Quarter 3: 1 City (Barbalha/CE) Increase trends: Quarter 1: 4 cities (Belém/PA, São Paulo/SP, Curitiba/PR, Caparaó/MG) Quarter 2: 2 cities (Belém/PA, Caparaó/MG) Quarter 3: 1 city (Belém/PA) Quarter 4: 2 cities (Belém (PA) and Manaus/AM)
PRCPTOT	4 cities with a trend of increase above 95% (Belém/PA, Cuiabá/MT, Manaus/AM, São Paulo/SP) 1 city with a falling trend with 95% (Cabrobó/PE)	Falling trends: Quarter 3: 1 City (Barbalha/CE) Increase trends: Quarter 1: 2 cities (Belém/PA and São Paulo/SP) Quarter 2: 2 cities (Belém/PA and Belo Horizonte/MG) Quarter 4: 2 cities with (Manaus/AM and Belém/PA)

Source: The authors (2023).

Constraints of our research include the utilization of data from only 11 Brazilian cities, which may not adequately represent each climate region of the entire country, and the analysis period limited to 1961-2019. Future studies can address these limitations, as well as explore other extreme indices and incorporate climate models to project upcoming trends and enhance our comprehension of climate extremes in Brazil.

The discernment of these climatic extremes is crucial for the formulation of effective public policies, to mitigate the resulting impacts on society. Such meteorological phenomena are intrinsically linked to changes in agricultural productivity and can precipitate natural disasters such as floods and landslides. In our analysis, we highlight the importance of a multidisciplinary and integrated approach to climate risk and disaster management, as addressed by Dalagnol et al. (2022). The finding that the lack of urban risk planning, mitigation, and adaptation strategies, in addition to the lack of investment in infrastructure, are key elements for the extension of impacts caused by extreme weather events, reinforces the relevance of our findings. This involves strategic planning in agriculture to maintain productivity under changing weather patterns, as well as implementing robust infrastructure projects and zoning regulations to minimize damage from severe weather events. The need to improve risk governance, through the organization of the role and responsibility of each institution that makes up the disaster defense system, and the use of green infrastructure, such as vegetated spaces, to reduce the probability and intensity of flash flood events, are prevention measures that are highly relevant to our study context. Civil society participation in building a population-centric, multi-health early warning system is a strategy that should be widely promoted and integrated into our policy recommendations. It is therefore essential to incorporate this understanding of climate extremes into planning and long-term risk management strategies to safeguard communities and sustain socio-economic development in the face of our evolving climate.

7 Conclusions

This paper presented an analysis that sought to identify trends of changes in indicators of climatic extremes in cities of 11 climatic regions in Brazil. The study considered data between 1961 and 2019. This work is an in-depth version of what was presented by Coelho et al. (2021), presenting as an additional detailed study by quartiles of the year, which allows us to identify the trends closest to the changes in the seasons.

The results obtained are in line with other studies in the literature, indicating an increase in maximum and minimum temperatures in all Brazilian climatic regions, in addition to an increase in the incidence of rainfall in some regions, such as Belem (PA) and Sao Paulo (SP).

The findings emphasize the importance of considering regional and temporal variations in climate analysis and have significant implications for water resource management and climate change adaptation strategies.

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Contributions of The authors

This article was prepared based on the contributions of all authors.

Interest conflicts

There is no conflict of interest.

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