

ANALYSIS OF VARIABILITY AND MONTHLY, SEASONAL AND ANNUAL TRENDS IN AIR TEMPERATURE IN BRAZIL

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Abstract: Temperature plays an important role in detecting climate change brought on by urbanization and industrialization. This study focuses on the variability and trends of the maximum annual, seasonal and monthly mean surface air temperature in Brazil during the period 1960-2020, three statistical tests, the Pettitt test, the Mann-Kendall sequential test (SQ-MK test) and the Mann-Kendall classification test (MK test) were used for the analysis. The results of the analysis of the entire period reveal a statistically significant upward trend in virtually every month and season of the year. A trend was also observed towards warmer years, with summer and spring significantly warmer and autumn and winter slightly warmer. Positive trends in average annual temperature were found throughout the period. For the entire region, average maximum temperatures tended to increase by approximately 0.012 °C per year.

Keywords: Air Temperature, Climate Change, Brazil, Mann-Kendall Test, Trends.

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ANÁLISE DA VARIABILIDADE E TENDÊNCIAS MENSAS, SAZONAIS E ANUAIS DA TEMPERATURA DO AR NO BRASIL

Resumo: A temperatura desempenha um papel importante na detecção das alterações climáticas provocadas pela urbanização e industrialização. Este estudo tem como objetivo verificar a variabilidade e tendências da temperatura média máxima anual, sazonal e mensal do ar superficial no Brasil durante o período 1960-2020. Três testes estatísticos, o teste de Pettitt, o teste sequencial de Mann-Kendall (teste SQ-MK) e o teste de classificação de Mann-Kendall (teste MK) foram utilizados para análise. Os resultados da análise de todo o período revelam um crescimento estatisticamente significativa em praticamente todos os meses e estações do ano. Observou-se também uma relação significativamente positiva para anos mais quentes, com o verão e a primavera significativamente mais quentes e o outono e o inverno ligeiramente mais quentes. Tendências positivas na temperatura média anual foram encontradas ao longo do período. Para toda a região, as temperaturas máximas médias aumentaram aproximadamente 0,012°C por ano.

Palavras-chave: Temperatura do Ar, Mudanças Climáticas, Brasil, Teste Mann-Kendall, Tendências.

ANÁLISIS DE VARIABILIDAD Y TENDENCIAS MENSUALES, ESTACIONALES Y ANUALES DE LA TEMPERATURA DEL AIRE EN BRASIL

Resumen: La temperatura juega un papel importante en la detección del cambio climático causado por la urbanización y la industrialización. Este estudio se objetivo en la variabilidad y tendencias de la temperatura media máxima anual, estacional y mensual del aire en superficie en Brasil durante el período 1960-2020, tres pruebas estadísticas, la prueba de Pettitt, la prueba secuencial de Mann-Kendall (prueba SQ-MK) y Para el análisis se utilizó la prueba de clasificación de Mann-Kendall (prueba MK). Los resultados del análisis de todo el período revelan una tendencia alcista estadísticamente significativa en prácticamente todos los meses y estaciones del año. También se observó una tendencia hacia años más cálidos, con veranos y primaveras significativamente más cálidos y otoños e inviernos ligeramente más cálidos. A lo largo del período se encontraron tendencias positivas en la temperatura media anual. Para toda la región, las temperaturas máximas promedio tendieron a aumentar aproximadamente 0,012°C por año.

Palabras clave: Temperatura del aire, Cambio climático, Brasil, Prueba de Mann-Kendall, Tendencias.



Introduction

Climate change has significant impacts on several regions of the world and affects both hydrometeorological characteristics and temperature patterns. Analysis of temperature trends is crucial to understanding global warming and its effects on monthly, seasonal and annual scales. These trends are usually studied using historical data sets, regardless of specific weather conditions.

In Brazil, Almeida et al. (2017) analyzed 47 locations in the Brazilian Legal Amazon and identified significant increasing trends of approximately 0.04 °C year⁻¹ in minimum and maximum air temperatures. Salviano et al. (2016) analyzed interpolated climatic data and reported statistically significant increases in mean air temperature over 36–78% of the Brazilian territory. Carvalho et al. (2020) evaluated temperature trends using data from 45 meteorological stations distributed throughout Brazil and concluded that the greatest increases occurred in Northeastern Brazil and in inland regions farther from the coast. These studies demonstrate that warming has occurred in different parts of Brazil; however, they differ considerably with respect to data sources, temporal coverage, spatial resolution, and analytical approaches, making direct comparisons difficult.

Oliveira et al. (2018) investigated climate change and change-point detection in temperature series in Northeastern Brazil using statistical methods to identify abrupt shifts associated with regional climate variability. Penereiro (2020) evaluated long-term trends in maximum temperature, minimum temperature and precipitation between 1961 and 2017 for several Brazilian locations and reported a predominance of increasing temperature trends, suggesting that urban growth and industrial development may have contributed to the observed climatic changes. Silva et al. (2023) analyzed maximum and minimum air temperature data for the State of Alagoas between 1980 and 2013 and identified statistically significant increases exceeding 1.0 °C per decade.

Although previous studies have documented significant warming trends in specific regions or localities of Brazil, a comprehensive assessment of monthly, seasonal and annual mean maximum air temperature using a homogeneous climatic database and a consistent statistical framework for the entire country is still limited. In addition, comparatively few studies have simultaneously evaluated

temporal trends, their magnitude, and possible change points using complementary non-parametric statistical methods.

Therefore, the objective of this study was to investigate the variability and monthly, seasonal and annual trends of mean maximum air temperature (T_{max}) in Brazil during the period 1960–2020 using the Climatic Research Unit Time Series (CRU TS v4.0) dataset. Temporal trends were evaluated using the Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests, the magnitude of significant trends was estimated using Sen's slope estimator, and possible abrupt changes were identified using Pettitt's test.

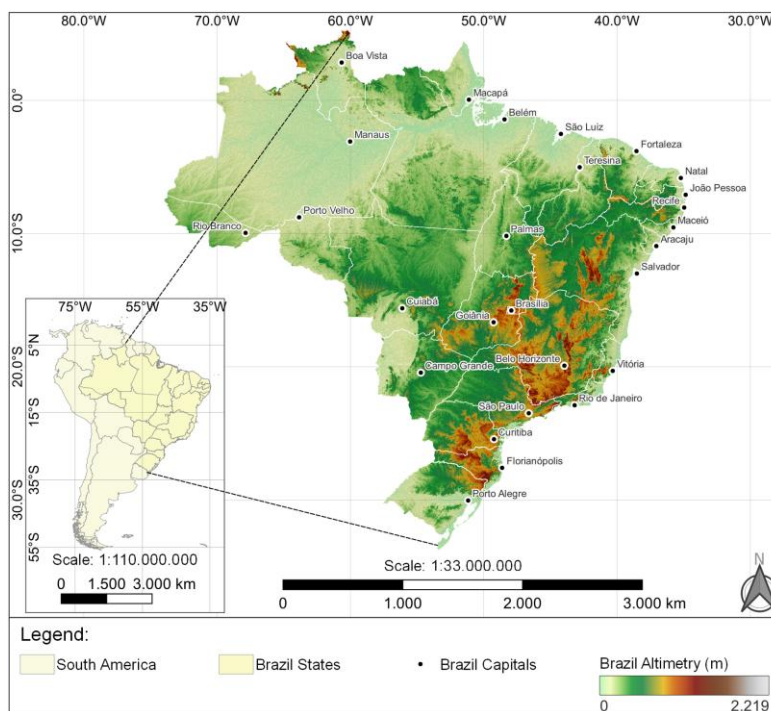
Materials and methods

Study Area and Data

Brazil has an area of approximately 8,515,767.0 km² and is located between the longitudes of 75°W and 35°W and the latitudes of 5°N and 30°S (Figure 1). The country comprises 5,569 municipalities and the Federal District, distributed into five official geopolitical regions: North, Northeast, Midwest, Southeast, and South (Brazilian Institute of Geography and Statistics – IBGE, 2021). The North Region is the largest, covering approximately 3,869,637.9 km², corresponding to 45.2% of the Brazilian territory, whereas the South Region is the smallest, with an area of approximately 575,316.0 km², corresponding to 6.8% of the national territory.

Figure 1 presents the geographical location of the 27 Brazilian state capitals together with the country's elevation.

Figure 1 - Location of the 27 Capitals of Brazil, altimetry (m)



Source: IBGE (2021) for administrative boundaries and SRTM digital elevation model. Prepared by the authors.

The 27 Brazilian state capitals were selected because they provide a homogeneous spatial distribution across the five official geopolitical regions and represent the principal urban centers of each state. This sampling strategy allows the evaluation of spatial and temporal patterns of air temperature over the entire Brazilian territory while ensuring a balanced regional representation.

Monthly mean maximum air temperature (Tmax) data covering the period from January 1960 to December 2020 were obtained from Version 4 of the Climatic Research Unit Time Series (CRU TS v4.0) dataset developed by the Climatic Research Unit (CRU), University of East Anglia, United Kingdom (Harris et al., 2020).

For each capital, a monthly Tmax time series was extracted from the corresponding $0.5^\circ \times 0.5^\circ$ CRU grid cell, resulting in 732 monthly observations (61 years $\times$ 12 months). Each capital was treated as an independent time series throughout the analyses, allowing the investigation of temporal variability and long-term temperature trends at local, regional, and national scales.

Climatic Dataset

Monthly mean maximum air temperature (Tmax) data covering the period from January 1960 to December 2020 were obtained from Version 4.07 of the Climatic Research Unit Time Series dataset (CRU TS v4.07), developed by the Climatic Research Unit (CRU), University of East Anglia, United Kingdom (Harris et al., 2020). The CRU TS dataset provides monthly gridded climatic variables at a spatial resolution of $0.5^\circ \times 0.5^\circ$ over the global land surface, excluding Antarctica, and is generated from quality-controlled meteorological observations interpolated using angular-distance weighting procedures (Harris et al., 2014; Harris et al., 2020).

For each of the 27 Brazilian state capitals, monthly Tmax values were extracted from the corresponding CRU grid cell according to the geographic coordinates of each capital, resulting in continuous time series composed of 732 monthly observations (61 years $\times$ 12 months).

To evaluate temperature variability at different temporal scales, the monthly series were aggregated into seasonal and annual series. Seasonal averages were calculated according to the climatological seasons of the Southern Hemisphere: summer (December–February), autumn (March–May), winter (June–August), and spring (September–November). Annual values were obtained as the arithmetic mean of the twelve monthly observations for each calendar year.

Each capital was considered an independent climatic time series. The resulting monthly, seasonal, and annual datasets constituted the basis for all subsequent statistical analyses, including descriptive statistics, hierarchical cluster analysis, Mann–Kendall (MK) and Modified Mann–Kendall (MMK) trend tests, Sen's slope estimation, and Pettitt change-point detection.

The use of the CRU TS dataset ensures temporal consistency and homogeneous spatial coverage over the entire Brazilian territory, allowing the comparison of long-term temperature variability among the 27 state capitals under the same methodological framework (Harris et al., 2014; Harris et al., 2020).

Hierarchical Cluster Analysis

Hierarchical cluster analysis (HCA) was performed to classify the 27 Brazilian state capitals according to the similarity of their annual mean maximum air temperature (Tmax) series during the period 1960–2020. Prior to clustering, the annual temperature series were organized into a data matrix in which each capital was represented by its temporal observations.

The dissimilarity matrix was computed using the Euclidean distance, and the hierarchical agglomerative clustering procedure was performed using Ward's minimum variance method (Ward, 1963). This method minimizes the within-cluster variance during the agglomeration process, producing compact and internally homogeneous groups.

The resulting dendrogram was used to define four statistical clusters (S1–S4). These clusters represent groups of capitals with similar temporal temperature behaviour and were subsequently used to organize the regional analyses presented in the Results section. Because they are statistical groups obtained from hierarchical clustering, S1–S4 should not be interpreted as the official Brazilian geopolitical regions.

The hierarchical cluster analysis was performed using the R statistical environment (R Core Team, 2024).

Trend Analysis

Temporal trends in monthly, seasonal, and annual mean maximum air temperature (Tmax) were evaluated using the non-parametric Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975). Because climatic time series frequently exhibit serial autocorrelation, the presence of lag-1 autocorrelation was evaluated prior to the trend analyses. Whenever statistically significant autocorrelation was detected ($p < 0.05$), the Modified Mann–Kendall (MMK) test proposed by Yue and Wang (2004) was applied to correct the variance of the original Mann–Kendall statistic without affecting the magnitude of the detected trend.

The null hypothesis (H0) assumes that the observations are independent and randomly ordered, indicating the absence of a monotonic trend. The alternative hypothesis (H1) assumes that a statistically significant increasing or decreasing monotonic trend exists in the time series.

The Mann–Kendall statistic (S) is calculated as:

(1)

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

where x_i and x_j represent observations at times i and j , respectively, n is the total number of observations, and sgn is the sign function defined as:

$$\text{sgn}(x_j - x_i) = \begin{cases} 1, & x_j > x_i \\ 0, & x_j = x_i \\ -1, & x_j < x_i \end{cases}$$

The statistic S represents the cumulative number of positive and negative differences among all possible pairs of observations. Positive values indicate increasing trends, whereas negative values indicate decreasing trends.

The variance of S is calculated as:

(2)

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

where m is the number of tied groups and t_i is the number of observations in the i-th tied group.

The standardized test statistic (Z) was subsequently calculated to evaluate the statistical significance of the detected trends. Statistical significance was assessed at the 5% probability level ($p < 0.05$). Positive Z values indicate increasing temperature trends, whereas negative Z values indicate decreasing trends.

Sen's Slope Estimator

Whenever statistically significant trends were detected, their magnitudes were quantified using Sen's slope estimator (Sen, 1968). This non-parametric estimator calculates the median slope among all possible pairs of observations and provides a robust estimate of the rate of temperature change over time, being relatively insensitive to outliers and non-normal data distributions.

For the present study, Sen's slope values were expressed in $^{\circ}\text{C year}^{-1}$. Positive slope values indicate increasing mean maximum air temperature, whereas negative values indicate decreasing temperature trends. Because the estimator is based on medians rather than least-squares regression, it is particularly suitable for hydroclimatic time series containing non-normal distributions or extreme observations (Yue and Wang, 2004; Sa'adi et al., 2019).

Pettitt Change-Point Test

Possible abrupt changes in the monthly, seasonal, and annual Tmax series were investigated using the non-parametric Pettitt test (Pettitt, 1979). This procedure identifies a single change point in a time series by testing whether two subsets of observations belong to the same statistical population.

The null hypothesis assumes that all observations originate from a homogeneous population with no abrupt change in the median. Rejection of the null hypothesis indicates the occurrence of a statistically significant change point separating two periods with distinct statistical characteristics.

The Pettitt statistic is given by:

(3)

$$K_t = \max |U_{t,n}|$$

where t represents the possible change point and n is the total number of observations.

The Mann-Whitney statistic is defined as:

(4)

$$U_{t,n} = \sum_{i=1}^t \sum_{j=t+1}^n \text{sgn}(x_i - x_j)$$

The year corresponding to the maximum absolute value of K_t was considered the most probable change point in each temperature series. Statistical significance was evaluated at the 5% probability level ($p < 0.05$).

Statistical Analyses

Descriptive statistics, including the mean, minimum, maximum, standard deviation, coefficient of variation, skewness, and kurtosis, were initially calculated to characterize the temporal variability of the monthly, seasonal, and annual Tmax series. Subsequently, the Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests were applied to detect monotonic trends, Sen's slope estimator was used to quantify the magnitude of statistically significant trends, and Pettitt's test was employed to identify possible abrupt changes in the temperature series.

All statistical analyses were performed using the R statistical computing environment (R Core Team, Vienna, Austria). Statistical significance was evaluated at the 5% probability level ($p < 0.05$). The results are presented as descriptive statistics, trend coefficients, significance levels, and graphical representations of monthly, seasonal, annual, regional, and national temperature variability.

Results

The descriptive statistics of the monthly, seasonal, and annual mean maximum air temperature (Tmax) series for Brazil during the period 1960–2020 are presented in Table 1. The statistical parameters include the mean, standard deviation (StDev), coefficient of variation (CV), minimum, maximum, range, skewness, and kurtosis, providing an overview of the temporal variability and distribution of the temperature series.

The monthly mean maximum air temperature ranged from 26.52 °C in July to 30.90 °C in January, while the annual mean Tmax was 29.90 °C with a standard deviation of 0.30 °C (Table 1). Monthly coefficients of variation ranged from 1.38% (March) to 1.72% (July), indicating low interannual variability throughout the study period. Skewness values varied between –0.29 and 0.35, suggesting that most monthly temperature distributions were approximately symmetric. Kurtosis values ranged from –0.53 to 0.40, indicating predominantly platykurtic distributions, although some months exhibited slightly leptokurtic behaviour. The complete descriptive statistics for the monthly, seasonal, and annual series are presented in Table 1.

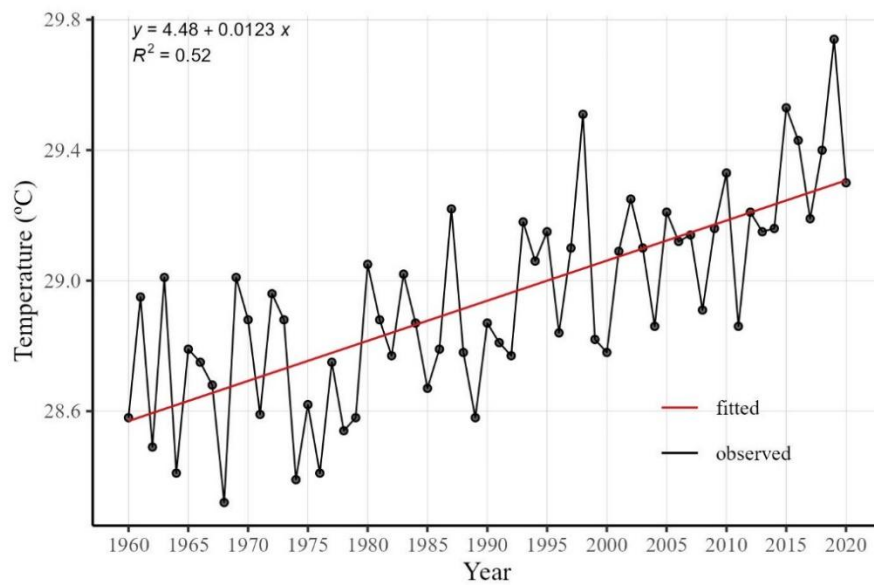
Table 1- Descriptive analysis of the average maximum temperatures for the capitals of Brazil, period 1960-2020.

Variable	Mean	StDev	CV%	Minimum	Maximum	Range	Skewness	Kurtosis
jan	29.82	0.43	1.43	28.96	30.90	1.94	0.21	-0.53
feb	29.76	0.42	1.4	28.87	30.81	1.938	0.32	0.17
mar	29.47	0.41	1.38	28.43	30.37	1.941	-0.1	-0.11
apr	28.92	0.46	1.58	27.90	30.07	2.17	0.22	0.04
may	27.99	0.47	1.67	26.65	29.29	2.642	0.06	0.34
jun	27.54	0.46	1.68	26.69	28.78	2.085	0.04	-0.42
jul	27.46	0.47	1.72	26.52	28.53	2.008	-0.29	-0.52
aug	28.23	0.41	1.45	27.34	29.16	1.824	0.17	-0.26
sept	28.98	0.49	1.71	28.22	30.05	1.828	0.35	-0.85
oct	29.50	0.48	1.63	28.39	30.44	2.055	-0.09	-0.29
nov	29.59	0.43	1.45	28.52	30.74	2.213	-0.02	0.4

dec	30.00	0.42	1.41	29.11	31.02	1.917	-0.14	-0.32
Summer	29.68	0.37	1.24	28.93	30.50	1.567	0.09	-0.39
Autumn	28.15	0.39	1.4	27.13	29.34	2.219	0.02	0.38
winter	28.22	0.37	1.32	27.50	28.98	1.482	0.14	-0.77
Spring	29.70	0.38	1.28	28.67	30.68	2.005	0.09	0.17

The results of the analysis of the point of change indicated that the point of change for the average annual flow was in the year 1993. As a result of the trend analysis, an increasing trend was found for the maximum annual mean temperature (Figure 2).

Figure 2 - Trend analysis of the annual average temperature of Brazil, period 1960-2020



For the maximum seasonal average temperature, change points were detected in 1993, 1974, 1989 and 1992 for summer and autumn, 1989 for spring 1992 for winter, respectively. The results of the trend analyses showed that the maximum average temperature has increasing trends for all seasons (Figure 3).

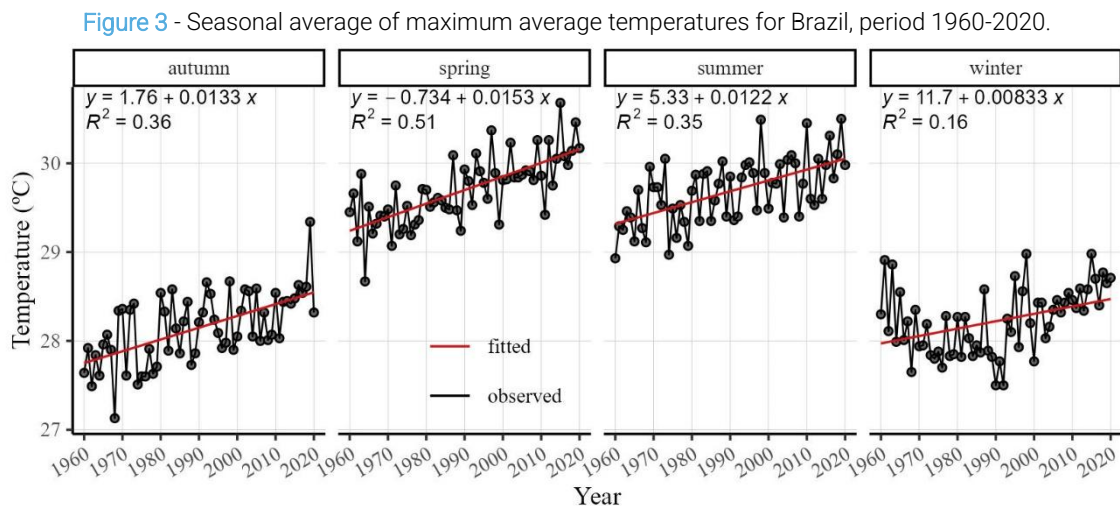
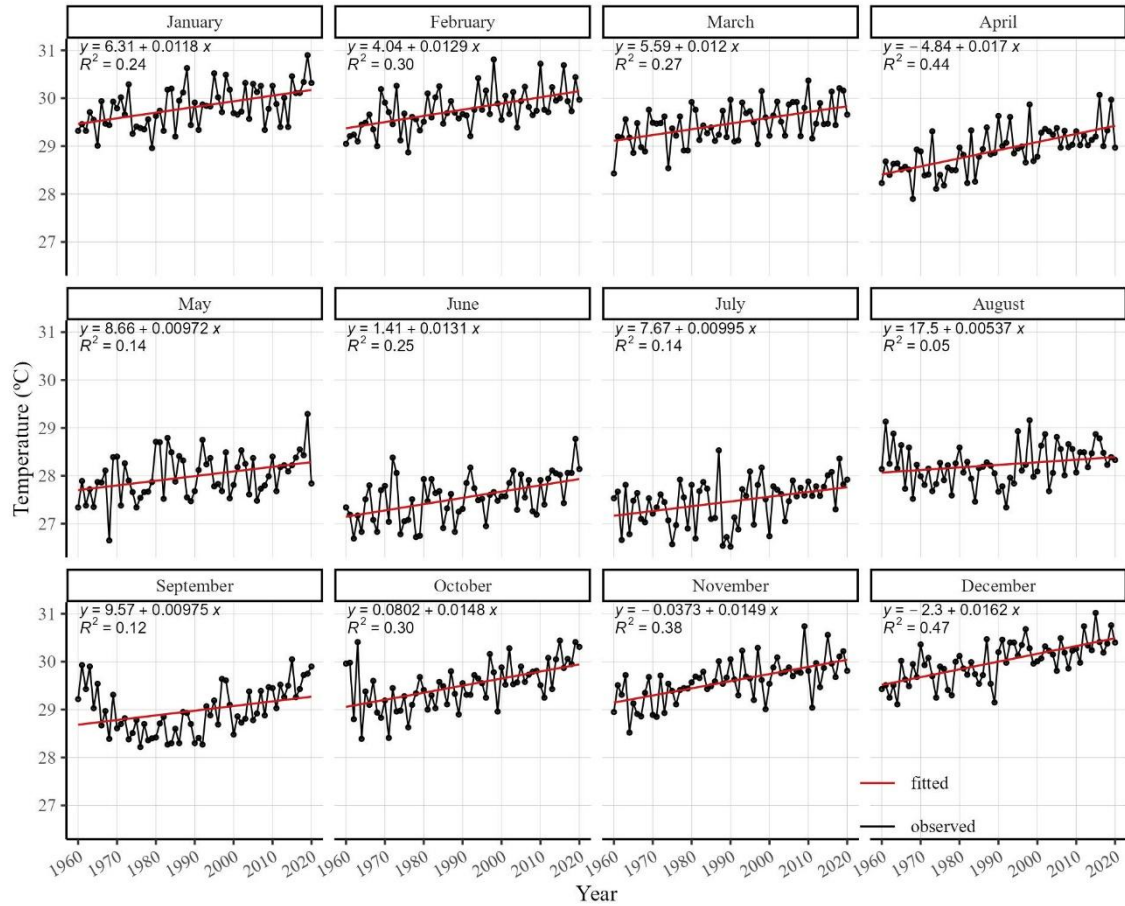


Figure 4 - Monthly average of maximum average temperatures for Brazil, period 1960-2020



The statistics of the Mann-Kendall Tmax test are given in Table 2. The statistically significant levels, 0.05 was used in this article. The nonparametric estimate of the magnitude of the slope, b , was calculated for the significant trends, which certify all trends in °C/year.

The behavior of Tmax was studied for individual months, seasons and annually, submitting them to the Mann-Kendall test. The results of the statistics of standardized test Z , significance level p -value and slope b (slop); which correspond to the trend of the temperature variables analyzed in this study are presented in Table 2. It should be noted that Tmax show a significant trend in most months.

Table 2 - Results of the Mann–Kendall (MK) trend test, Sen's slope estimator, and Pettitt change-point test for the annual mean maximum air temperature (Tmax) series grouped according to the hierarchical cluster analysis (Clusters S1–S4)

Region	Capital	MK Z	MK p-value	Sen's slope (°C year ⁻¹)	95% CI	Pettitt U	Change point (year)
S1	Aracaju	2.352	0.019	0.004	0.000–0.010	328	1982
S1	Campo Grande	3.379	<0.001	0.011	0.004–0.017	643	1993
S1	Fortaleza	4.306	<0.001	0.010	0.005–0.014	572	1978
S1	Goiânia	7.044	<0.001	0.023	0.018–0.029	875	1993
S1	João Pessoa	–0.342	0.732	–0.001	–0.006–0.003	274	1999
S1	Natal	1.400	0.162	0.003	–0.002–0.007	339	1978
S1	Recife	–1.307	0.191	–0.003	–0.008–0.001	368	1998
S1	Salvador	3.696	<0.001	0.009	0.003–0.013	519	1992
S2	Belém	5.962	<0.001	0.021	0.015–0.027	706	1980
S2	Boa Vista	3.647	<0.001	0.012	0.005–0.020	727	1996
S2	Cuiabá	1.469	0.142	0.004	–0.004–0.012	475	1993
S2	Macapá	4.512	<0.001	0.016	0.009–0.022	504	1986
S2	Manaus	5.041	<0.001	0.016	0.010–0.022	823	1996
S2	Palmas	3.286	0.001	0.012	0.004–0.019	482	1997
S2	Porto Velho	1.431	0.152	0.007	–0.008–0.017	472	1970
S2	Rio Branco	–0.510	0.610	–0.003	–0.012–0.005	447	1970
S2	São Luís	7.443	<0.001	0.021	0.017–0.025	791	1989
S2	Teresina	6.347	<0.001	0.027	0.020–0.034	783	1989
S3	Belo Horizonte	3.049	0.002	0.009	0.002–0.017	417	1992
S3	Brasília	3.528	<0.001	0.015	0.006–0.024	605	1993
S3	Maceió	–1.207	0.227	–0.004	–0.009–0.001	351	1990
S3	Rio de Janeiro	3.217	0.001	0.009	0.002–0.015	508	1992
S3	Vitória	2.595	0.009	0.006	0.000–0.012	345	1985
S4	Curitiba	5.072	<0.001	0.015	0.010–0.022	632	1990
S4	Florianópolis	3.989	<0.001	0.012	0.005–0.018	538	2000
S4	Porto Alegre	3.248	0.001	0.008	0.002–0.013	522	2000
S4	São Paulo	5.121	<0.001	0.016	0.010–0.023	688	1991

Notes: S1–S4 represent the clusters obtained from the hierarchical cluster analysis based on the similarity of the annual mean maximum air temperature series. These groups do not correspond to the official Brazilian geopolitical regions. MK = Mann–Kendall test; Z = standardized Mann–Kendall statistic; Sen's slope = median rate of temperature change (°C year⁻¹); 95% CI = 95% confidence interval of Sen's slope; Pettitt U = Pettitt test statistic; Change point = year of the abrupt change identified by Pettitt's test.

(B) Monthly, Seasonal and Annual Series

Series	MK Z	p-value	Sen's slope (°C year ⁻¹)	Pettitt U	Pettitt p-value	Change point (Year)
January	3.697	<0.001	0.012	526	0.002	1983
February	4.619	<0.001	0.012	577	<0.001	1993
March	3.716	<0.001	0.011	518	0.002	1993
April	5.397	<0.001	0.016	756	<0.001	1987
May	2.695	0.007	0.009	401	0.031	1980
June	3.915	<0.001	0.014	495	0.003	1991
July	3.081	0.002	0.009	477	0.005	1993
August	1.799	0.072	0.006	444	0.012	1995
September	3.063	0.002	0.013	558	<0.001	1993
October	4.780	<0.001	0.018	606	<0.001	1993
November	5.396	<0.001	0.014	637	<0.001	1987
December	5.521	<0.001	0.016	761	<0.001	1990
Annual	5.995	<0.001	0.012	755	<0.001	1993
Summer	4.868	<0.001	0.012	595	<0.001	1993
Autumn	4.756	<0.001	0.013	575	<0.001	1990
Winter	3.280	0.001	0.010	606	<0.001	1995
Spring	6.081	<0.001	0.015	764	<0.001	1990

Regional trends

Table 2 shows the results of the trend analysis for the entire region of Brazil. In the annual series, there was a very strong significant warming trend of approximately 0.012°C per year for maximum mean temperatures (Figure 1, Table 2). The specific factors related to observed trends in climate change may vary depending on geographic and temporal context. However, some factors may be associated with the mentioned climate trends, such as:

Changes in land use: Changes in vegetation cover and land use, such as deforestation, urbanization and conversion of forests into agricultural areas, can have a significant impact on regional climate conditions. The removal of forests, for example, can lead to changes in energy balance and evapotranspiration, directly affecting temperature and precipitation patterns.

Increased CO₂ concentration: Increased carbon dioxide (CO₂) emissions from burning fossil fuels and other human activities contribute to global warming. CO₂ is one of the main greenhouse gases, trapping heat in the atmosphere and leading to an increase in the average temperature of the earth's surface. The increase in CO₂ concentration in the atmosphere may contribute to the observed warming trends.

Natural climate variability: Natural climate variability, such as weather phenomena such as El Niño and La Niña, can play an important role in observed trends. These periodic weather events can change temperature and precipitation patterns in different regions of Brazil and influence short-term weather trends. It is important to emphasize that these factors do not act in isolation but interact in complex ways. For example, changes in land use can affect the concentration of CO₂ in the atmosphere, while natural climate variability can amplify or attenuate the effects of anthropogenic changes.

It is essential to carry out more in-depth and comprehensive studies to better understand the contribution of each of these factors to specific climate trends in the region of Brazil. These investigations must consider the interaction between ecological, social and economic factors to provide a more complete understanding of the implications of climate change in the region.

Annual Temperature Trends

Figure 2 presents the annual mean maximum air temperature (T_{max}) series for Brazil during the period 1960–2020 together with the corresponding linear trend and the change point identified by Pettitt's test. The annual T_{max} exhibited a statistically significant increasing trend according to both the Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests (Table 2). Sen's slope estimator indicated a warming rate of approximately $0.012\text{ }^{\circ}\text{C year}^{-1}$, corresponding to an increase of approximately $0.72\text{ }^{\circ}\text{C}$ over the 61-year study period.

The Pettitt test identified a statistically significant change point in 1993 ($p < 0.05$), indicating a shift from a relatively cooler to a warmer temperature regime. Annual mean maximum air temperature values after 1993 were consistently higher than those observed during the first part of the study period (Figure 2).

The positive trend identified in the annual series is consistent with the monthly and seasonal analyses presented in the following sections, indicating that the warming signal was persistent throughout the study period.

Seasonal temperature trends

Figure 3 presents the seasonal mean maximum air temperature (T_{max}) series for Brazil during the period 1960–2020 together with the corresponding trend analyses. The Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests indicated statistically significant increasing trends for all seasons, although the magnitude of the trends differed among them (Table 2).

Summer exhibited the highest warming rate, followed by spring, whereas autumn and winter presented smaller but still statistically significant positive trends. Sen's slope estimator indicated positive temperature changes for all seasons, confirming a persistent warming pattern throughout the study period.

The Pettitt test identified statistically significant change points for the seasonal series, indicating shifts from cooler to warmer temperature conditions during the study period. The years in which these changes occurred are presented in Table 2 and are consistent with the increasing trends identified by the MK and MMK tests.

Overall, the seasonal analyses demonstrate that warming occurred throughout the year, although with different magnitudes among the four climatological seasons.

Monthly temperature trends

The behavior of the average maximum temperature was also studied for individual months, submitting them to the Mann–Kendall test. The results are also presented in Table 2 and Figure 4.

Figure 4 presents the monthly mean maximum air temperature (T_{max}) series for Brazil during the period 1960–2020, together with the corresponding linear trends. The results of the Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests, Sen's slope estimator, and Pettitt's change-point test are summarized in Table 2.

The monthly T_{max} series exhibited statistically significant increasing trends ($p < 0.05$) for almost all months of the year. August was the only month with a non-significant Mann–Kendall result ($p = 0.072$; Table 2), whereas all remaining months exhibited statistically significant positive trends ($p < 0.05$). Sen's slope estimates indicate positive warming rates throughout the annual cycle, ranging from approximately 0.006 to 0.018 $^{\circ}\text{C year}^{-1}$, with the highest values observed during October, November and December.

The monthly analyses indicate that the observed warming was not restricted to a particular season but occurred throughout most of the year, although with different magnitudes among the individual months. The corresponding change points identified by Pettitt's test are also presented in Table 2.

Possible mechanisms associated with the observed warming include increases in greenhouse gas concentrations, biomass burning, and land-use changes, particularly in regions affected by agricultural expansion and deforestation. These processes have been identified in previous studies as important drivers of regional warming in Brazil (Souza et al., 2021; Souza et al., 2022; Reis et al., 2022).

Biomass burning releases substantial amounts of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), enhancing the greenhouse effect and contributing to increased air temperatures. In addition, land-use changes modify the surface energy balance and evapotranspiration, which may further intensify regional warming. The combined effects of these processes have been reported in several studies investigating climate variability in Brazil (Souza et al., 2021; Souza et al., 2022; Reis et al., 2022).

Surface air temperature is one of the principal variables used in weather forecasting and climate studies because it reflects climate variability at local, regional, and global scales (Ghasemi, 2015). Although increasing temperature trends have been documented worldwide, the accurate quantification of these trends remains an active research topic (Gil-Alana, 2018). Therefore, the monthly analyses presented here provide additional evidence of the persistence of warming throughout Brazil during the study period.

Brazilian Regions temperature trends

The regional analyses of monthly, seasonal, and annual mean maximum air temperature (T_{max}) for the five Brazilian geopolitical regions are presented in Table 2 and Figures 5 and 6. The Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests indicated positive temperature trends in all regions during the period 1960–2020. These trends were statistically significant for the North, Northeast, and Midwest regions, whereas the Southeast and South regions also exhibited positive trends with lower magnitudes. Sen's slope estimates and the corresponding Pettitt change points are summarized in Table 2.

The Northeast Region also exhibited a statistically significant warming trend throughout the study period. According to Table 2, the largest increases were observed for the capitals of São Luís and Teresina, corresponding to Maranhão and Piauí, respectively. These results are consistent with previous studies that associated regional warming with land-use and land-cover changes, urbanization, desertification processes, and natural climate variability associated with the El Niño–Southern Oscillation (ENSO) (Almeida et al., 2017; Alves et al., 2016; Costa et al., 2021; Libonati et al., 2021; Marengo et al., 2020a; Marengo et al., 2022).

Positive temperature trends were also identified for the Midwest Region. The highest warming rates were observed for the capitals of Cuiabá, Campo Grande, Goiânia, and Brasília (Table 2). Previous studies have related the observed warming in Central Brazil to agricultural expansion, land-use conversion, and increasing greenhouse gas emissions associated with regional economic development (Marengo et al., 2022; Costa et al., 2021).

Discussion

The present study identified a consistent warming pattern in the monthly, seasonal, and annual mean maximum air temperature (T_{max}) across Brazil during the period 1960–2020. The Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests indicated statistically significant increasing trends for most monthly and seasonal series, while Sen's slope estimator indicated an average warming rate of approximately $0.012\text{ }^{\circ}\text{C year}^{-1}$. These findings are consistent with previous studies reporting widespread warming over different regions of Brazil (Almeida et al., 2017; Salviano et al., 2016; Carvalho et al., 2020; Penereiro, 2020).

The regional analyses revealed differences in the magnitude of the warming trends among the five Brazilian geopolitical regions. The North, Northeast, and Midwest regions exhibited the strongest statistically significant warming trends, whereas the Southeast and South also presented increasing trends of lower magnitude. These regional differences are consistent with previous investigations showing that climatic variability in Brazil is strongly influenced by land-use and land-cover change, deforestation, agricultural expansion, urbanization, and regional atmospheric circulation (Marengo et al., 2018b; Gatti et al., 2021; Marengo et al., 2022; Libonati et al., 2021).

The pronounced warming observed in the North Region agrees with studies demonstrating that the Amazon has experienced longer and warmer dry seasons, increasing deforestation rates, and more frequent biomass-burning events during recent decades (Marengo et al., 2018b; Gatti et al., 2021; Da Silva Cruz et al., 2022). These processes modify the surface energy balance and contribute to regional warming by reducing evapotranspiration and increasing sensible heat fluxes.

Similarly, the warming identified in the Northeast and Midwest regions is consistent with previous studies relating increasing air temperature to land-use change, agricultural expansion, urbanization, and changes in regional precipitation regimes (Almeida et al., 2017; Costa et al., 2021; Marengo et al., 2022). However, the present study does not establish direct causal relationships between these processes and the observed temperature trends. Instead, the results indicate that the detected warming is compatible with mechanisms previously described in the literature.

Surface air temperature is one of the principal indicators of climate variability because it integrates the effects of atmospheric circulation, land-surface processes, and radiative forcing at different temporal and spatial scales (Ghasemi, 2015). Consequently, the identification of statistically significant warming trends over most Brazilian regions provides additional evidence that recent climate change has affected not only annual temperatures but also monthly and seasonal climatic variability. Similar conclusions have been reported by Regoto et al. (2021), who identified increasing frequencies of warm temperature extremes throughout Brazil, reinforcing the evidence of regional-scale warming.

Although the warming rates identified in this study are consistent with previous investigations conducted in Brazil, comparisons with global warming indicators should be made with caution because they involve different variables, spatial scales, and reference periods. The present study evaluated regional trends in monthly mean maximum air temperature, whereas global assessments generally refer to global mean surface temperature anomalies relative to a pre-industrial baseline. Therefore, the Brazilian regional trends reported here should be interpreted within their specific climatological context rather than directly compared with global temperature-change estimates.

One limitation of the present study is that the analyses were based on the CRU TS v4.0 gridded dataset. Although this database has been extensively validated and widely applied in climatological studies (Harris et al., 2020), local-scale variability may not be fully represented because of the spatial interpolation procedures and the $0.5^{\circ} \times 0.5^{\circ}$ spatial resolution. Nevertheless, the temporal consistency

and spatial coverage of the CRU TS dataset make it suitable for evaluating long-term temperature variability at national and regional scales.

Conclusions

The monthly, seasonal, and annual analyses demonstrated a significant increase in maximum air temperature throughout Brazil during the period analyzed.

The present study investigated the temporal variability and trends of monthly, seasonal, and annual mean maximum air temperature (Tmax) in Brazil during the period 1960–2020 using the Climatic Research Unit Time Series (CRU TS v4.0) dataset. The combined application of the Mann–Kendall (MK), Modified Mann–Kendall (MMK), Sen's slope estimator, and Pettitt test provided a comprehensive assessment of the magnitude, statistical significance, and temporal evolution of temperature trends.

The results demonstrated statistically significant positive trends in annual, seasonal, and most monthly temperature series, indicating a persistent warming pattern throughout the study period. Sen's slope estimator indicated an average annual warming rate of approximately 0.012 °C year⁻¹, while Pettitt's test identified significant change points for most series during the late 1980s and early 1990s, indicating a transition to warmer climatic conditions.

Regional analyses showed that warming occurred throughout Brazil, although with different magnitudes among the five geopolitical regions. The North, Northeast, and Midwest regions exhibited the strongest warming trends, whereas the Southeast and South also presented positive but less pronounced increases in mean maximum air temperature.

These findings contribute to the understanding of the spatial and temporal variability of air temperature in Brazil and provide additional evidence of the widespread warming observed during the last decades. The results also provide useful information for climate monitoring, environmental planning, water resource management, agricultural adaptation, and the development of strategies to mitigate the impacts of climate change.

Future studies should evaluate the observed trends using ground-based meteorological station data, compare different gridded climate datasets, and investigate the influence of large-scale climate variability, land-use change, and urbanization on regional temperature patterns.

DATA AVAILABILITY: The datasets analyzed in the present study are available at <https://crudata.uea.ac.uk/cru/>. CRU TS4.0.1.. For statistical analysis, the free software R (<https://cran.r-project.org/bin/windows/base/>) was used.

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