Half a century of air temperature changes in the capitals of the Legal Amazon

Meio século de mudanças na temperatura do ar nas capitais da Amazônia Legal

Medio siglo de cambios en la temperatura del aire en las capitales de la Amazonía Legal

Un demi-siècle de changements de température de l'air dans les capitales de l'Amazonie légale

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Abstract

Rising temperatures have a significant impact on urban centers in the Amazon. This study aimed to analyze the temporal evolution and warming trends of air temperature in the capitals of the Legal Amazon over the last half century (1970-2024), with an emphasis on identifying warming trends. ERA5 reanalysis data were used, applying the Mann-Kendall test, Sen estimator, and Pettitt test to identify trends and change points. All capitals showed statistically significant warming trends (Z_{MK} 5.78 to 7.23, p<0.0001), with annual increase rates ranging from 0.019°C to 0.032°C. Change points were predominantly identified between the 1990s and 2000s.

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Comparison between pre- and post-change periods revealed significant temperature increases, with amplitudes between 0.52°C (São Luís) and 0.91°C (Boa Vista), indicating substantial warming and spatial heterogeneity, with greater intensity in the north of the region and in transition zones. The study provides robust evidence of persistent warming in Amazonian capitals, contributing crucial data for climate adaptation policies and urban planning in this sensitive region.

Keywords: Legal Amazon; climate change; urban warming.

Resumo

O aumento das temperaturas impacta significativamente os centros urbanos da Amazônia. Este estudo teve como objetivo analisar a evolução temporal e as tendências de aquecimento da temperatura do ar nas capitais da Amazônia Legal no último meio século (1970-2024), com ênfase na identificação de tendências de aquecimento. Utilizaram-se dados de reanálise ERA5, aplicando os testes de Mann-Kendall, estimador de Sen e teste de Pettitt para identificar tendências e pontos de mudança. Todas as capitais apresentaram tendências de aquecimento estatisticamente significativas (Z_{MK} 5,78 a 7,23, p<0,0001), com taxas de aumento anual variando de 0,019°C a 0,032°C. Pontos de mudança foram predominantemente identificados entre as décadas de 1990 e 2000. A comparação entre os períodos pré e pós-mudança revelou aumentos significativos de temperatura, com amplitudes entre 0,52°C (São Luís) e 0,91°C (Boa Vista), indicando aquecimento substancial e heterogeneidade espacial, com maior intensidade no norte da região e em zonas de transição. O estudo fornece evidências robustas do aquecimento persistente nas capitais amazônicas, contribuindo com dados cruciais para políticas de adaptação climática e planejamento urbano nesta região sensível.

Palavras-chave: Amazônia Legal; mudanças climáticas; aquecimento urbano.

Resumen

El aumento de las temperaturas impacta significativamente los centros urbanos de la Amazonía. Este estudio tuvo como objetivo analizar la evolución temporal y las tendencias de calentamiento de la temperatura del aire en las capitales de la Amazonía Legal en el último medio siglo (1970-2024), con énfasis en la identificación de tendencias de calentamiento. Se utilizaron datos de reanálisis ERA5, aplicando las pruebas de Mann-Kendall, el estimador de Sen y la prueba de Pettitt para identificar tendencias y puntos de cambio. Todas las capitales presentaron tendencias de calentamiento estadísticamente significativas (Z_MK 5,78 a 7,23, p<0,0001), con tasas de aumento anual que varían entre 0,019°C y 0,032°C. Los puntos de cambio fueron predominantemente identificados entre las décadas de 1990 y 2000. La comparación entre los períodos pre y post-cambio reveló aumentos significativos de temperatura, con amplitudes entre 0,52°C (São Luís) y 0,91°C (Boa Vista), lo que indica un calentamiento sustancial y heterogeneidad espacial, con mayor intensidad en el norte de la región y en zonas de transición. El estudio proporciona pruebas sólidas del calentamiento persistente en las capitales amazónicas, contribuyendo con datos cruciales para políticas de adaptación climática y planificación urbana en esta región sensible.

Palabras clave: Amazonía Legal; cambio climático; calentamiento urbano.

Résumé

L'augmentation des températures impacte de manière significative les centres urbains de l'Amazonie. Cette étude visait à analyser l'évolution temporelle et les tendances de réchauffement de la température de l'air dans les capitales de l'Amazonie légale au cours du dernier demi-siècle (1970-2024), en mettant l'accent sur l'identification des tendances de réchauffement. Des données de réanalyse ERA5 ont été utilisées, en appliquant les tests de Mann-Kendall, l'estimateur de Sen et le test de Pettitt pour identifier les tendances et les points de changement. Toutes les capitales ont montré des tendances de réchauffement statistiquement significatives (Z_MK 5,78 à 7,23, $p<0{,}0001$), avec des taux d'augmentation annuels variant de 0,019°C à 0,032°C. Les points de changement ont été principalement identifiés entre les décennies de 1990 et 2000. La comparaison entre les périodes avant et après le changement a révélé des augmentations significatives de température, avec des amplitudes allant de 0,52°C (São Luís) à 0,91°C (Boa Vista), indiquant un réchauffement substantiel et une hétérogénéité spatiale, avec une plus grande intensité au nord de la région et dans les zones de transition. L'étude fournit des preuves solides du réchauffement persistant dans les capitales amazoniens, contribuant ainsi à fournir des données cruciales pour les politiques d'adaptation climatique et la planification urbaine dans cette région sensible.

Mots-clés: Amazonie légale ; changement climatique ; réchauffement urbain.

1 INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), in its Sixth Assessment Report (AR6), air temperatures are rising globally as a consequence of climate change, with particularly intensified effects in urban environments, where warming is potentiated by the formation of heat islands and rapid urbanization (IPCC, 2023; Shahfahad *et al.*, 2024). According to Liu *et al.* (2022), the warming of urban surfaces varies according to the size of the cities and their geographical location, generally being more pronounced in larger urban centers, where population density and the urbanization process contribute significantly to the rise in temperatures. This phenomenon is aggravated in areas with compact infrastructure and scarcity of vegetation, which compromises natural cooling mechanisms (Cheng *et al.*, 2019; Hou; Estoque, 2020; Song; Park, 2021). In this scenario, it becomes crucial to understand how these dynamics manifest themselves in ecologically sensitive regions, such as the Amazon (Ferreira, Sávio José Filgueiras *et al.*, 2021; Furtado; Pereira; de Souza, 2024), where urban expansion can accentuate local and regional climatic effects.

The Amazon has experienced significant climate changes over the past five decades, most notably a persistent and significant increase in air temperature (Carvalho *et al.*, 2020; Da Silva *et al.*, 2019; Lucas *et al.*, 2021; Ritchie *et al.*, 2022). This continuous warming directly affects the region's main urban centers, amplifying challenges related to public health, infrastructure, and quality of life (Alves de Oliveira *et al.*, 2021; Ferreira, Mariana Abou Mourad *et al.*, 2023). Rising temperatures are one of the clearest expressions of climate change on a global and regional scale, with profound impacts on ecosystems, biodiversity, and the human populations that occupy this vast and sensitive portion of the national territory, directly affecting the well-being of urban communities (Tham *et al.*, 2020). Given this scenario, it becomes essential to investigate warming trends in Amazonian capitals in order to support public policies and guide urban planning, promoting effective adaptation and mitigation strategies in the face of adverse climate effects (Marengo *et al*., 2018).

Established scientific studies, such as those by Marengo *et al.* (2024) and Nobre *et al.* (2016), have repeatedly demonstrated the increase in surface temperatures across the vast Amazon region. This process is strongly associated with changes in land use and land cover, driven primarily by deforestation for agricultural, livestock, and infrastructure expansion. However, a review of the literature reveals that most research on Amazonian thermal dynamics has focused on rural areas or transition zones between forest and anthropized areas. While these approaches are essential for understanding the impacts of forest conversion, they ultimately leave significant gaps in understanding warming in urbanized areas. The capitals of the Amazonian states, which play central roles in regional administration, economy, and demography, concentrate a significant and growing portion of the population. This population density, coupled with disordered urban growth and the intensification of the heat island effect (Raiol *et al.*, 2024), makes these cities particularly vulnerable to the consequences of climate change.

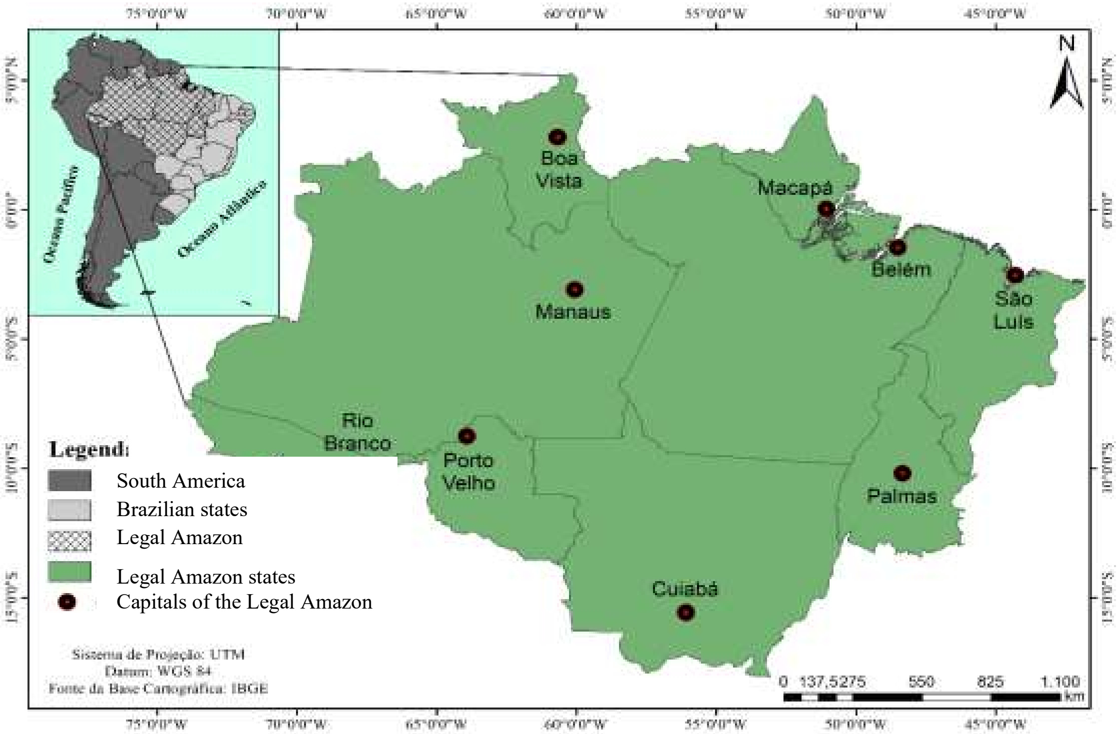
Although numerous studies have already documented rising temperatures in tropical regions, such as the Amazon (Almeida *et al.*, 2017; Da Silva *et al.*, 2019; de Souza *et al.*, 2025; Marengo *et al.*, 2024; Ritchie *et al.*, 2022), a significant gap persists in the continuous monitoring and in-depth analysis of warming in urban areas of the region, especially in the capital cities. These locations, increasingly impacted by changes in land use and the intensification of urban effects on the climate, require methodological approaches that consider their microclimatic specificities. In light of this context, the importance of advancing the investigation of changes and trends in air temperature in the capital cities of the Legal Amazon, which concentrate a growing portion of the regional population and present unique urban characteristics, becomes evident. The analysis of thermal evolution over half a century allows not only to quantify the magnitude of warming, but also to identify temporal and spatial patterns that contribute to the formulation of effective adaptive responses. Investigations with this focus are therefore fundamental to filling gaps in scientific literature and providing technical support for sustainable urban planning and the development of public policies aimed at mitigating the climate impacts on Amazonian urban centers. Thus, this study aims to analyze the temporal evolution of air temperature and its trend in the capitals of the Legal Amazon during the last half-century (1970-2024), with an emphasis on identifying warming trends.

2 MATERIALS AND METHODS

2.1 STUDY AREA

The study area encompasses the nine capitals of the Legal Amazon (Figure 1): Belém – PA, Boa Vista – RR, Cuiabá – MT, Macapá – AP, Manaus – AM, Palmas – TO, Porto Velho – RO, Rio Branco – AC, and São Luís – MA. These cities present distinct climatic, environmental, and urban characteristics, representing the socio-environmental diversity of the region. According to the last Brazilian Institute of Geography and Statistics (IBGE) census conducted in 2022 (IBGE, 2022), the total population of the 9 capitals (7,040,045) is equivalent to approximately 3.5% of the total population of Brazil (203,080,756 inhabitants).

Figure 1 – Geographic location of the state capitals of the Legal Amazon



Source: The authors (2025).

Based on the Köppen-Geiger 1936 climate classification (Köppen; Geiger, 1936; Lima *et al.*, 2023; Rahimi; Laux; Khalili, 2020), the Legal Amazon region has a climate type classified as "A" (corresponding to a tropical climate, characterized by average monthly temperatures always above 18°C throughout the year. This climate group is also characterized by high relative humidity and high rainfall, although the distribution of rainfall throughout the year may vary according to the subcategory). It is subdivided into three more specific types: type "*Af*" (humid tropical climate, without a dry season; all months with precipitation > 60 mm and average temperatures > 18°C); "*Am*" (monsoon tropical climate, with a short dry season; driest month with precipitation < 60 mm); and "*Aw*" (seasonal tropical climate, with a dry season in winter and rainfall concentrated in summer; driest month with precipitation < 60 mm). Throughout the year, air temperature does not show great variability, except in southern Amazonia. This occurs due to the influence of passing frontal systems (Marengo; Nobre; Culf, 1997).

In this region, there are two main meteorological systems that drive the high amount of rainfall between the months of December and April (Reboita *et al.*, 2010). In its northern portion, the ITCZ (Intertropical Convergence Zone) is active, reaching its southernmost position (~4°S) between February and April. On the other hand, in the southern part of the Legal Amazon, in a NW-SE direction, from southwestern Amazonas to southeastern Mato Grosso, the SACZ (South Atlantic Convergence Zone) predominates, with its peak activity between December and February (Liebmann *et al.*, 1999).

2.2 CLIMATOLOGICAL AIR TEMPERATURE DATABASE

The air temperature variable at 2 meters used in this study was extracted from the ERA5 reanalysis, developed by the ECMWF (European Centre for Medium-Range Weather Forecasts) and made available by the C3S (Copernicus Climate Change Service) (Bell *et al.*, 2021; Hersbach *et al.*, 2020). ERA5 represents the fifth generation of global atmospheric reanalysis and provides consistent, high-quality estimates of various meteorological and climate variables, combining observations (from surface, balloons, satellites, and other sources) with sophisticated numerical models through a 4D-Var data assimilation system. (Gustafsson, 2007; Lorenc; Rawlins, 2005).

The air temperature at 2 meters (variable name: 2m_temperature, or t2m) refers to the estimate of the free air temperature at a height of 2 meters above the ground or vegetation surface. This estimate is derived from extrapolating the lowest pressure levels of the atmospheric model to the 2-meter level, considering local terrain and land cover conditions. Temperature values are provided in Kelvin (K) units, converted to degrees Celsius (°C) when necessary for easier interpretation and visualization. The spatial resolution of ERA5 is 0.25° × 0.25° latitude/longitude, which corresponds to approximately 31 km at the equator. The temporal resolution is hourly, with records available every 1 hour (UTC), allowing for detailed analyses of diurnal variations and extreme events. Data are available globally since 1950 (with more robust operational quality from 1979 onwards).

2.3 STATISTICAL PROCEDURES

2.3.1 The Mann-Kendall Test

The Mann-Kendall (MK) test (Kendall, 1955; Mann, 1945) is a widely used non-parametric test for detecting monotonic trends in time series. It assesses the significance of a trend without requiring the data to be normally distributed. The test begins by calculating the S statistic using the following equation (Equation 1):

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

where n is the total number of data points; x_j e x_i are the data values in the time series j and i ($j > i$), respectively, and $sgn(x_j - x_i)$ is the sign function, which can be calculated by the following equation (Equation 2):

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

A positive value of *S* indicates an upward trend, and a negative value indicates a downward trend. The statistical distribution *S* is approximately normal when *n* > 10. The mean of *S* is zero, and the variance can be calculated as follows (Equation 3):

$$\mathrm{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)\right] \quad (3)$$

where *n* is the number of data points; *m* is the number of tied groups (a data set with the same value is considered a tied group); and t_i denotes the number of ties in extent *i*. In the case where the sample size, $n > 10$, the values of *S* and "Var" (*S*) are used to calculate the standard test Z_{MK} as follows (Equation 4):

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, & se\ S > 0 \\ 0, & se\ S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, & se\ S < 0 \end{cases} \quad (4)$$

The Z_{MK} score follows a normal distribution. Considering a significance level of α=0.05, corresponding to a 95% confidence interval for a two-tailed test, the critical values are -1.96 and +1.96. Thus, when the Z_{MK} value is negative and its absolute value exceeds 1.96, there is a statistically significant decreasing trend. On the other hand, if Z_{MK} is positive and greater than 1.96, the trend is increasing and significant. Z_{MK} values between -1.96 and +1.96 indicate no significant trend at the 5% level.

2.3.2 The Sen's slope estimator

The MK test, in conjunction with Sen's slope estimator (Sen, 1968), allows us to estimate the direction and magnitude of the trend, considering the conventional significance level of 0.05 (95%). This estimator calculates the median slope of all possible combinations between *N* pairs of points in the time series (Equation 5):

$$Q_i = \frac{X_j + X_k}{j - k}, i = 1, 2, 3, \ldots, N \quad (5)$$

where X_j and X_k are the data values at times *j* and *k (j > k)*, respectively. In Equation 5, $j > k$, the median of these *N* Q_i values is represented by the slope of the Sen estimate. The median of the Q_i values represents the magnitude of the trend. A positive value of the Sen slope indicates an increasing trend, while a negative value indicates a decreasing trend (Faquseh; Grossi, 2024).

2.3.3 The Pettitt Test

The Pettitt test (Pettitt, 1979) is a non-parametric test used to detect a significant change (or turning point) in a time series. It is particularly useful when you want to identify a point where the median of the series changes, without assuming a specific distribution for the data. In this study, the Pettitt test will be used to indicate in which year the turning point occurred, to separate the time series into two distinct periods, as used in several climatological studies (Ahmadi *et al.*, 2018; Mallakpour; Villarini, 2016; Rybski; Neumann, 2011; Serinaldi; Kilsby, 2016; Verma; Prasad; Verma, 2022; Zarenistanak; Dhorde; KripalaniI, 2014). This test is presented in such a way that *k* is the candidate index for a turning point (or break point) and the values x_1, x_2, ..., x_n

are values from the time series, arranged in ascending order (Equation 6). The absolute value is used because we are interested in the intensity of the change, regardless of the direction:

$$k = \left| \max_{k} \sum_{i=1}^{k} \sum_{j=i+1}^{n} sgn(x_j - x_i) \right|, 1 < k < n \quad (6)$$

where $sgn(x_j - x_i)$ is the sign function (Equation 7).

$$sgn(x_j - x_i) = \begin{cases} +1, & se\ x_j - x_i > 0 \\ 0, & se\ x_j - x_i = 0 \\ -1, & se\ x_j - x_i < 0 \end{cases} \quad (7)$$

The point of change in the series is located in the Pettitt test when k reaches its maximum value, provided the statistic is significant. The probability of significance of k is approximated to $p \leq 0.05$ with (Equation 8)

$$p \approx 2exp\left(\frac{-6k^2}{n^3 + n^2}\right) \quad (8)$$

As long as the *p*-value is greater than the specified significance level α (0.05), the null hypothesis (H_0 indicates homogeneous data) can be accepted and there is no change point in the data series. Conversely, for *p*-values less than α (0.05), the null hypothesis is rejected and the alternative hypothesis (H_1 indicates a change has occurred) is considered.

2.4 WARMING STRIPES

To illustrate the annual temperature anomalies relative to the 1971-2000 average of the ERA5 data, the methodology developed by Ed Hawkins (Hawkins *et al.*, 2025) was chosen. This is a simple and impactful way to visualize warming in the capitals of the Legal Amazon; its strength lies in the visual clarity of the trend. In Hawkins' visualizations, the use of warm and cool colors clearly and accessibly communicates climate change. Warm colors (shades of red) indicate warming, while cool colors (shades of blue) suggest cooling; the darker the color, the greater the magnitude of the anomaly, facilitating comprehension by diverse audiences (O’Connor, 2023).

2.5 DATA PROCESSING

To acquire the ERA5 annual average temperature data, a script was developed in the Python language (Mehare; Anilkumar; Usmani, 2023). In simple terms, the code automates the download, processing, and export of annual air temperature data at 2 meters for a specific point (defined by latitude and longitude), using ERA5 reanalysis. It accesses the Copernicus Climate Data Store API to obtain monthly temperature averages since 1970, calculates anomalies based on the climatology of the period 1971–2000, and exports the results in CSV files, both in annual resolution.

Using the Python programming language, statistics were calculated for the Mann-Kendall test, Sen's slope, and the Pettitt test. In summary, the steps adopted in the code performed a trend analysis and change detection in annual time series of average temperature, based on data in CSV format. It uses the Pettitt test to identify points of abrupt change, the Mann-Kendall test to verify the presence of a monotonic trend, and Sen's slope to estimate the rate of temperature variation over time.

The Warming Stripes were developed with code to graphically represent the annual air temperature anomalies of the capitals of the states in the Legal Amazon, between 1970 and 2024, based on ERA5 data. This code used a color gradient from blue (negative anomalies) to red (positive), assigning a color to each year according to the magnitude of the anomaly, composing a final high-resolution figure for climate communication and dissemination.

Finally, annual temperature trend graphs were created in Microsoft Excel, based on the results obtained from the Pettitt and Mann-Kendall statistical tests. In Excel, line graphs representing the temperature time series were created, with the addition of visual elements such as the year of change detected, allowing for a clear and accessible interpretation of climate patterns over time. This approach combined the robustness of statistical analyses with the graphical flexibility of Excel for presentation and scientific communication purposes.

4 RESULTS AND DISCUSSION

4.1 STATISTICAL ANALYSIS

Table 1 presents the results of the Z_{MK} statistic, the decline of Sen, and the p-value associated with the adopted statistics for the annual time series of air temperature at 2 meters in the analyzed capitals. The results of the Z_{MK} test revealed significant increasing trends ($p < 0.0001$) in all capitals of the Legal Amazon, confirming regional warming throughout the evaluated period, evidencing the presence of consistent and non-random warming in the time series. These results are consistent with recent research that points to an increase in air temperature in the Amazon (Almeida *et al.*, 2017; Da Silva *et al.*, 2019; Dias *et al.*, 2021; Victoria *et al.*, 1998).

Z_{MK} values ranged from 5.78 (Cuiabá) to 7.23 (Macapá), with the highest values observed in the cities of Macapá (Z_{MK} = 7.23) and Belém (Z_{MK} = 7.06), indicating more pronounced and consistent warming trends. The Sen slope, which estimates the annual rate of change, ranged from 0.019°C/year (São Luís) to 0.032°C/year (Boa Vista), reflecting a significant increase in average temperatures over the years. The high statistical significance, combined with moderate to high slopes, reinforces the robustness of the trends detected. Although São Luís presented the lowest Sen slope, the Z_{MK} value (6.43) suggests that this trend, although less intense, is highly consistent over time.

The analysis of warming trends in the capitals of Northern Brazil, evidenced by high Z_{MK} values and positive Sen slope rates, corroborates broader studies on climate change in the Amazon region. Research encompassing multiple locations and longer time series, using robust statistical methodologies such as the Mann-Kendall test, has also identified a predominant pattern of increasing average temperatures, particularly pronounced since the 1990s (Penereiro *et al.*, 2018). This convergence of results, both at the level of specific capitals and on a regional scale, underscores the consistency of the observed warming phenomenon, reinforcing the perception that the Amazon is an area particularly sensitive to global and regional climate change.

Table 1 – Results of the Mann–Kendall test (Z_{MK}), Sen decline and associated p-value, for annual temperature time series from 1970-2024

City	Z_{MK}	Sen decline (°C/year)	p-value
Belém	7.06	0.027	<0.0001
Boa Vista	6.43	0.032	<0.0001
Cuiabá	5.78	0.023	<0.0001
Macapá	7.23	0.027	<0.0001
Manaus	6.11	0.023	<0.0001
Palmas	5.92	0.025	<0.0001
Porto Velho	6.87	0.024	<0.0001
Rio Branco	5.98	0.021	<0.0001
São Luís	6.43	0.019	<0.0001

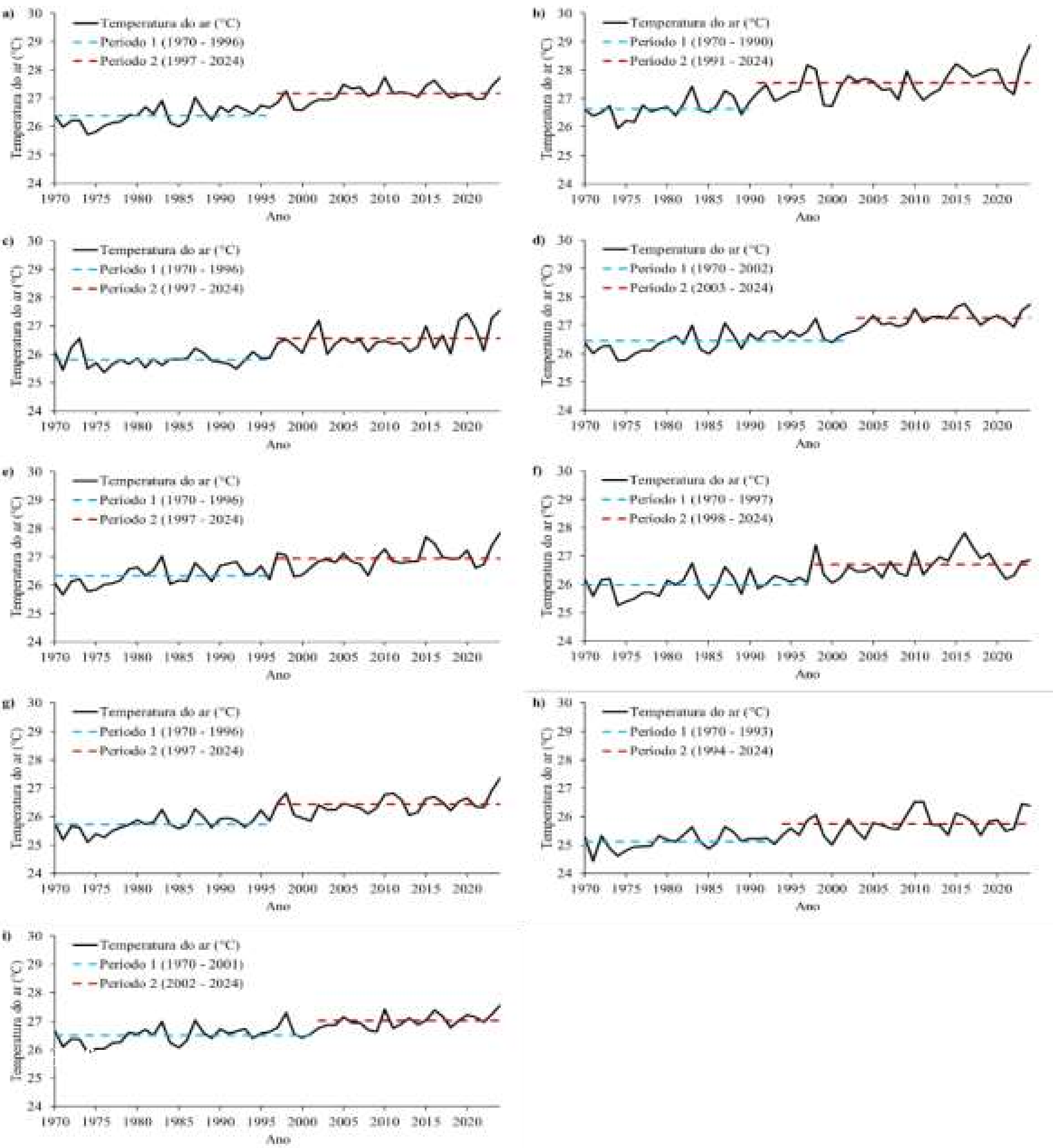
Source: The authors (2025).

The detection of statistically significant warming trends, such as those presented in Table 1, aligns with IPCC projections and observations, which point to a warming of the global climate system (IPCC, 2023). Although natural variability, including phenomena such as El Niño, can influence interannual and seasonal trends (Jiménez-Muñoz *et al.*, 2016; Li *et al.*, 2011; Moura *et al.*, 2019), the consistency of long-term trends suggests a strong component associated with anthropogenic climate change and land-use changes in the region (Almeida *et al.*, 2017). Understanding these trends and their potential drivers is crucial for the development and implementation of effective public policies and adaptation strategies that consider the specific vulnerabilities of each locality, given a scenario of evident warming trends (Green; Armstrong; Soon, 2009).

It is worth highlighting that the Z_{MK} values and Sen's slope did not show direct proportionality, corroborating the complementary nature of these metrics. While the Mann-Kendall test detects the existence and statistical significance of the trend, Sen's slope quantifies its magnitude (Aditya; Gusmayanti; Sudrajat, 2021). Furthermore, as observed by Yue, Pilon, and Cavadias (2002), although the Mann-Kendall test is effective in indicating the existence of monotonic trends in time series, it does not provide information on the rate of change, a role played by Sen's slope. This combined approach is especially useful in climate studies, where the trend can be statistically significant even with subtle variations (i.e., with a low slope), as verified in the case of São Luís. Thus, locations with greater statistical consistency are not always those with a higher rate of warming, which emphasizes the need for joint interpretation of these statistics.

Figure 2 illustrates the time series (1970–2024) of air temperature and the division of this series into two distinct periods, after applying the Pettitt test, for the capitals of the Legal Amazon. The Pettitt test allowed the identification of change points in the time series, suggesting a significant change in temperature behavior from the 1990s onwards. Most cities showed a change point in 1997 (Belém, Cuiabá, Manaus, Porto Velho), with exceptions such as Boa Vista (1991), Rio Branco (1994), Palmas (1998), São Luís (2002) and Macapá (2003). These results indicate an intensification of warming from the mid-1990s onwards in much of the region.

Figure 2 – Graphical representation of the annual temperature series (1970-2024) for Belém (a), Boa Vista (b), Cuiabá (c), Macapá (d), Manaus (e), Palmas (f), Porto Velho (g), Rio Branco (h) and São Luís (i). The dashed lines indicate the results found by the Pettitt test, where the blue colors indicate Period 1 (before the change) and the red colors indicate Period 2 (after the change)



Source: The authors (2025).

The identification of change points in temperature time series, predominantly in the 1990s and early 2000s, as detected by the Pettitt test, provides further evidence on the dynamics of warming in the Legal Amazon. The concentration of change points in this specific period suggests an inflection point or acceleration in the regional warming process, aligning with observations from other studies that also point to the 1990s as a key period for the intensification of positive temperature trends in the Legal Amazon. A study by Bodas Terassi et al. (2024) reveals that, during the 1990s and 2000s, there was an abrupt change, or pattern break, in climate data related to extreme temperatures. This change was not gradual, but rather a discontinuity, indicating that something significant may have influenced the climate during this period; the accelerated urbanization process (more buildings, more asphalt, less vegetation) may have altered the local microclimate, contributing to increased temperatures or a higher frequency of thermal extremes.

The change in the temperature regime from the identified tipping points may be associated with a combination of factors, including the intensification of the greenhouse effect on a global scale, natural climate variability, and regional changes in land use and land cover, such as deforestation (Bodas Terassi et al., 2024). Studies indicate that the climate changes observed in the Legal Amazon, including the increase in temperatures, are consistent with global warming (IPCC, 2023; Harris; Huntingford; Cox, 2008). Tipping point analysis, as performed with the Pettitt test, is fundamental to understanding not only the magnitude of the warming trend but also its temporal evolution, identifying periods of more accelerated changes that can significantly impact ecosystems and local populations, requiring adjustments in response and coping strategies.

Complementing Figure 2, Table 2 presents the long-term averages of annual temperatures (1970–2024) for the capitals of the Legal Amazon, segmented into two distinct periods, identified by the Pettitt test. The results reinforce the trend of increasing average annual temperatures in the capitals of the Legal Amazon, showing a consistent increase in average annual temperatures in all capitals between the two distinct periods. The observed variations (range between periods) ranged from 0.52°C in São Luís to 0.91°C in Boa Vista, indicating significant warming over the last few decades.

The largest temperature variations were observed in Boa Vista (0.91°C), Macapá (0.81°C), and Belém (0.80°C), all located in the northern part of the region, suggesting a possible intensification of the effects of global warming in this sub-region. In contrast, São Luís (0.52°C) and Rio Branco (0.63°C) showed the smallest variations, although still significant from a climatic point of view. The capital of Mato Grosso, Cuiabá, stood out for showing an increase of 0.75°C. This amplitude, for example, aligns with the observation that Amazon-Cerrado transition areas may experience more pronounced climate changes due to the combination of climatic and anthropogenic influences, corroborating studies that point to a more pronounced warming in transition areas between the Cerrado and the Amazon rainforest (Bodas Terassi *et al.*, 2024; Joseph; Souza; Sabino, 2021; Marengo *et al.*, 2022).

Table 2 – Long-term averages (1970-2024) of annual temperature series for the capitals of the Legal Amazon region during the different periods identified by the Pettitt test

City	Period 1	Period 2	Variation
Belém	26.4°C	27.2°C	0.80°C
Boa Vista	26.4°C	27.5°C	0.91°C
Cuiabá	25.8°C	26.6°C	0.75°C
Macapá	26.4°C	27.3°C	0.81°C
Manaus	26.3°C	26.9°C	0.62°C
Palmas	26.0°C	26.7°C	0.73°C
Porto Velho	25.7°C	26.4°C	0.71°C
Rio Branco	25.1°C	25.7°C	0.63°C
São Luís	26.5°C	27.0°C	0.52°C

Source: The authors (2025).

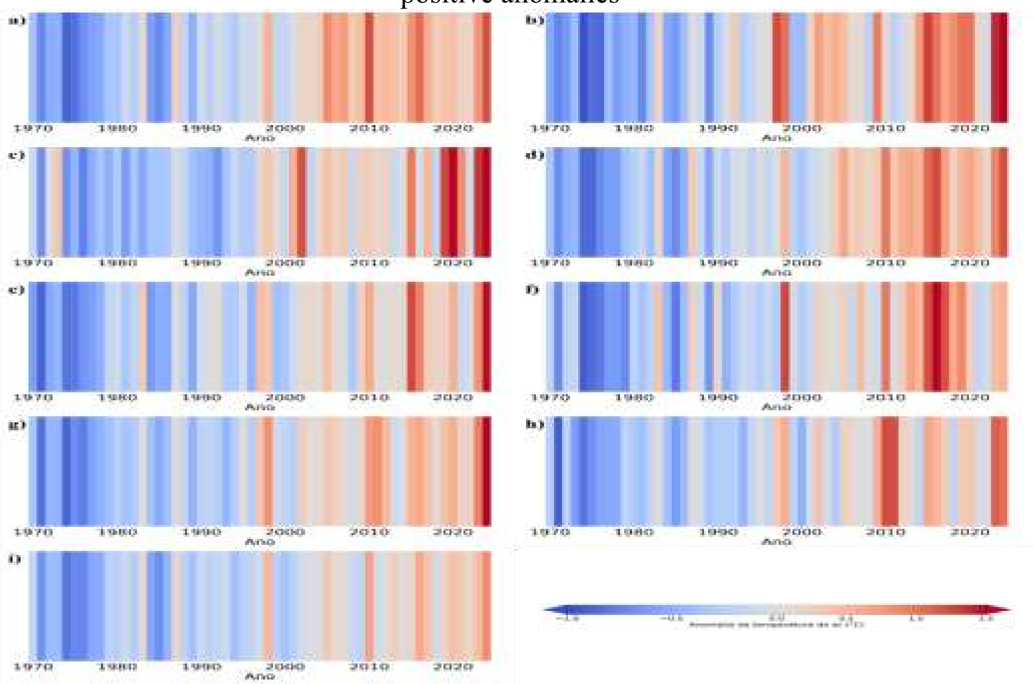
The comparative analysis of average temperatures between Periods 1 and 2 (Table 2) quantifies the magnitude of post-tipping point warming in each capital city. The observed range, varying from 0.52°C to 0.91°C, represents a substantial increase in the average annual temperature over a period of a few decades, reinforcing the robustness of the warming signal in the region. The spatial heterogeneity of the warming ranges, with higher values in the North (Boa Vista, Macapá, Belém) and in transition areas such as Cuiabá, suggests the influence of regional factors modulating the response to global warming.

4.3 WARMING STRIPES

Based on the warming stripes generated from annual air temperature anomalies (1970–2024) for the capitals of the Legal Amazon (Figure 3), a clear and consistent warming trend is observed over the last five decades. The graphs reveal a striking visual transition from bluish tones (negative anomalies) to reddish tones (positive anomalies), indicating a gradual and continuous increase in average annual temperatures in all the capitals analyzed. A predominance of bluish tones is observed until the mid-1980s, followed by a progressive increase in the frequency and intensity of reddish tones, indicating persistent positive anomalies from the 1990s onwards. This pattern intensifies in the 2000s and 2010s, reflecting an accelerated regional warming process.

Among the capital cities analyzed, Boa Vista presents one of the most striking warming trends, with anomalies exceeding +1.5°C in 2024, a value that represents the peak of the time series for this location. Other capital cities, such as Cuiabá, Macapá, and Belém, also recorded anomalies exceeding +1.0°C in several recent years. Capital cities located in the western and northeastern portions of the Legal Amazon, such as Rio Branco, Porto Velho, and São Luís, also demonstrated a gradual increase in positive anomalies, especially after the year 2000. The year 2024 stands out as one of the hottest in the entire time series for most capital cities, with a positive anomaly of around +1.4°C, which may be associated with the intensification of large-scale climatic phenomena, such as the El Niño phenomenon (Espinoza *et al.*, 2024; Santos de Lima *et al.*, 2024), in addition to the global warming trend.

Figure 3 – Warming stripes of air temperature anomalies from annual series (1970-2024) for Belém (a), Boa Vista (b), Cuiabá (c), Macapá (d), Manaus (e), Palmas (f), Porto Velho (g), Rio Branco (h) and São Luís (i). Colors in shades of blue indicate negative anomalies, while colors in shades of red indicate positive anomalies



Source: The authors (2025).

4 CONCLUSIONS

In summary, the results point to a regional scenario of significant and progressive warming in the Amazonian capitals, with important variations in both the intensity and statistical consistency of the trends. The results obtained through the application of the Mann-Kendall test, Sen estimator, and Pettitt test unequivocally evidenced a consistent and statistically significant warming process in all the capitals analyzed. The identification of change points by the Pettitt test allowed the series to be segmented into two distinct periods, revealing that most capitals experienced a significant change in thermal behavior from the 1990s onwards, especially in 1997, the year in which four capitals (Belém, Cuiabá, Manaus, and Porto Velho) presented breakpoints.

These results contribute to filling gaps in the scientific literature on thermal dynamics in Amazonian urban centers, offering a detailed characterization of the temporal evolution and magnitude of warming in the region's capitals. The contributions of the results can range from public health and urban thermal comfort issues to aspects related to energy demand and infrastructure planning. These findings reinforce the importance of regionalized climate adaptation strategies, considering the particularities of each capital city analyzed. These data highlight the importance of continuous monitoring of climatic variables and the implementation of public policies for adaptation and mitigation in the face of observed warming. This represents a growing challenge for public managers and urban planners, demanding specific adaptive mitigation strategies that consider the climatic and socio-environmental particularities of each location.

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