

Heat wave events in the capitals of Northern Brazil

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Abstract

Extreme weather events are atypical atmospheric conditions that can affect multiple sectors of society. Among them, heat waves are persistent episodes of elevated air temperature with significant environmental, social, and public health implications. This study evaluated the occurrence, frequency, duration, and intensity of heat waves in the capitals of Northern Brazil from 1980 to 2018. Daily maximum and minimum air temperature records from conventional weather stations of the Brazilian National Institute of Meteorology and the Brazilian Air Force Meteorology Network underwent consistency checks, and missing data were filled in using multiple imputation. Heat waves were identified with the CTX90pct and CTN90pct indices, based on the calendar-day 90th percentile for the 1980-2010 reference period, using a 15-day moving window and a minimum duration of three consecutive days. Intensity was assessed using Exceedance Degree-Days. A total of 825 heat-wave events were identified with CTX90pct and 806 with CTN90pct. Belém and Manaus concentrated the highest numbers of events. Frequency followed the annual behavior observed for occurrence, with some years exceeding 40% of days under heat-wave conditions in most capitals. Mean duration was approximately 4.4 days, whereas annual mean intensity ranged from 8.0 °C to 14.0 °C. The results show marked spatial and interannual variability and indicate an increase in heat-wave occurrence since the beginning of the 21st century, reinforcing the need for regionalized climate-risk studies and adaptation policies in Northern Brazil.

Keywords: Amazon, climate variability, extreme weather events, heat waves, urban heat island.

Ocorrência de eventos de ondas de calor nas capitais da região Norte do Brasil

Resumo

Eventos climáticos extremos são condições atmosféricas atípicas que podem afetar diversos setores da sociedade. Entre eles, destacam-se as ondas de calor, caracterizadas por episódios persistentes de temperaturas elevadas e importantes implicações ambientais, sociais e de saúde pública. Este estudo avaliou a ocorrência, frequência, duração e intensidade das ondas de calor nas capitais da região Norte do Brasil no período de 1980 a 2018. Foram utilizados registros diários de temperatura máxima e mínima do ar de estações meteorológicas convencionais do Instituto Nacional de Meteorologia e da Rede de Meteorologia do Comando da Aeronáutica. Os dados foram submetidos à análise de consistência e os registros faltantes foram preenchidos por imputação múltipla. As ondas de calor foram identificadas pelos índices CTX90pct e CTN90pct, com base no percentil 90 diário do período de referência 1980-2010, janela móvel de 15 dias e duração mínima de três dias consecutivos. A intensidade foi avaliada por graus-dia de excedência. Foram identificados 825 eventos pelo CTX90pct e 806 pelo CTN90pct, com maiores números de episódios em Belém e Manaus. A frequência acompanhou o padrão anual da ocorrência, com alguns anos registrando mais de 40% dos dias em condição de onda de calor na maioria das capitais. A duração média foi de aproximadamente 4,4 dias e a intensidade média anual variou entre 8,0 °C e 14,0 °C. Os resultados evidenciam forte variabilidade espacial e interanual e indicam aumento da ocorrência de ondas de calor desde o início do século XXI, reforçando a necessidade de estudos regionalizados e políticas de adaptação na Amazônia brasileira.

Palavras-chave: Amazônia, eventos climáticos extremos, ilha de calor urbana, ondas de calor, variabilidade climática.

1. Introduction

Natural disasters can be understood as the result of rare or extreme natural phenomena acting on a social system and producing losses that exceed the coping capacity of affected populations. In the atmospheric context, extreme weather and climate events are uncommon conditions that can generate impacts on infrastructure, agriculture, health, and economic activities. Heat waves are among the most relevant of these events because they develop gradually, are not

always perceived as an immediate hazard, and may cause direct and indirect impacts on human well-being (Perkins, 2015; Mora et al., 2017).

Although heat waves are widely recognized as hazardous, there is no single universal definition for them. In climate studies, they are commonly defined as periods of at least three consecutive days during which air temperature remains above a climatological threshold. Percentile-based indices are particularly useful because they account for local climate conditions and the seasonal cycle, enabling comparisons among regions with different thermal regimes (Perkins & Alexander, 2013; Geirinhas et al., 2018). Maximum and minimum air temperatures can be used separately to characterize daytime and nighttime heat-wave events, respectively.

The occurrence and persistence of heat waves are influenced by both local and large-scale climatic processes. In tropical South America and Amazonia, heat extremes may be modulated by ocean-atmosphere variability, including the El Niño–Southern Oscillation (ENSO) and sea surface temperature anomalies in the tropical Atlantic. These mechanisms can alter atmospheric circulation, convection, cloudiness, moisture transport, and rainfall distribution, favoring drought conditions and increasing the persistence of anomalously high temperatures. Major Amazon drought episodes, such as those observed in 2005, 2010, and 2015/2016, have been associated with anomalous sea surface temperature patterns in the Atlantic and Pacific Oceans and with strong climatic anomalies in the Amazon Basin (Lewis et al., 2011; Jiménez-Muñoz et al., 2016).

The relationship between drought and heat waves is especially relevant in the Amazonian context. During drought periods, reduced cloud cover, lower soil moisture, and changes in the surface energy balance can intensify near-surface warming and contribute to the development of persistent hot conditions. Compound drought and heat-wave events may also increase fire risk, affect ecosystems, and exacerbate public health impacts, particularly in socially vulnerable areas (Libonati et al., 2022; Silva Junior et al., 2019). Therefore, understanding heat waves in Northern Brazil requires considering not only local temperature anomalies but also broader atmospheric variability and oceanic forcing mechanisms.

The impacts of heat waves may occur directly, through heat stress, dehydration, heat exhaustion, and worsening of pre-existing diseases, or indirectly, through reductions in labor productivity, increased pressure on water and electricity systems, and higher fire risk when heat coincides with drought. These impacts are especially concerning in tropical regions, where high background temperatures make anomalous events more difficult to perceive and where social vulnerability can increase exposure and reduce adaptive capacity (Libonati et al., 2022; Ballarin et al., 2024).

Studies on heat waves in Brazil have increased in recent years, including analyses of climatic and synoptic characteristics in several Brazilian cities and national-scale assessments of trends in cold and heat waves (Geirinhas et al., 2018; Bitencourt et al., 2020). However, the territorial extent and environmental diversity of Brazil still require more regionalized analyses. Northern Brazil, dominated by the Amazon biome and characterized by high humidity, high temperatures, rapid urban growth in some capitals, and important socioeconomic contrasts, remains underrepresented in the literature. This gap is particularly important because the region is exposed to both local urbanization processes and large-scale climate variability associated with ENSO, tropical Atlantic anomalies, and Amazon droughts.

In this context, the objective of the present study was to evaluate the main characteristics of heat waves recorded in the capitals of Northern Brazil from 1980 to 2018. The analysis focused on occurrence, annual frequency, duration, and intensity, using indices based on daily maximum and minimum air temperature.

2. Material and Methods

2.1 Study area

The study was conducted in the capitals of Northern Brazil (Figure 1). The region covers approximately 3,853,676.948 km², with an estimated population of 18.4 million inhabitants and a population density of 4.78 inhabitants per km² (IBGE, 2020). The region is predominantly covered by equatorial broadleaf forest, although Cerrado areas are also present in Pará, Roraima, Rondônia, and much of Tocantins (Ministério do Meio Ambiente, 2010).

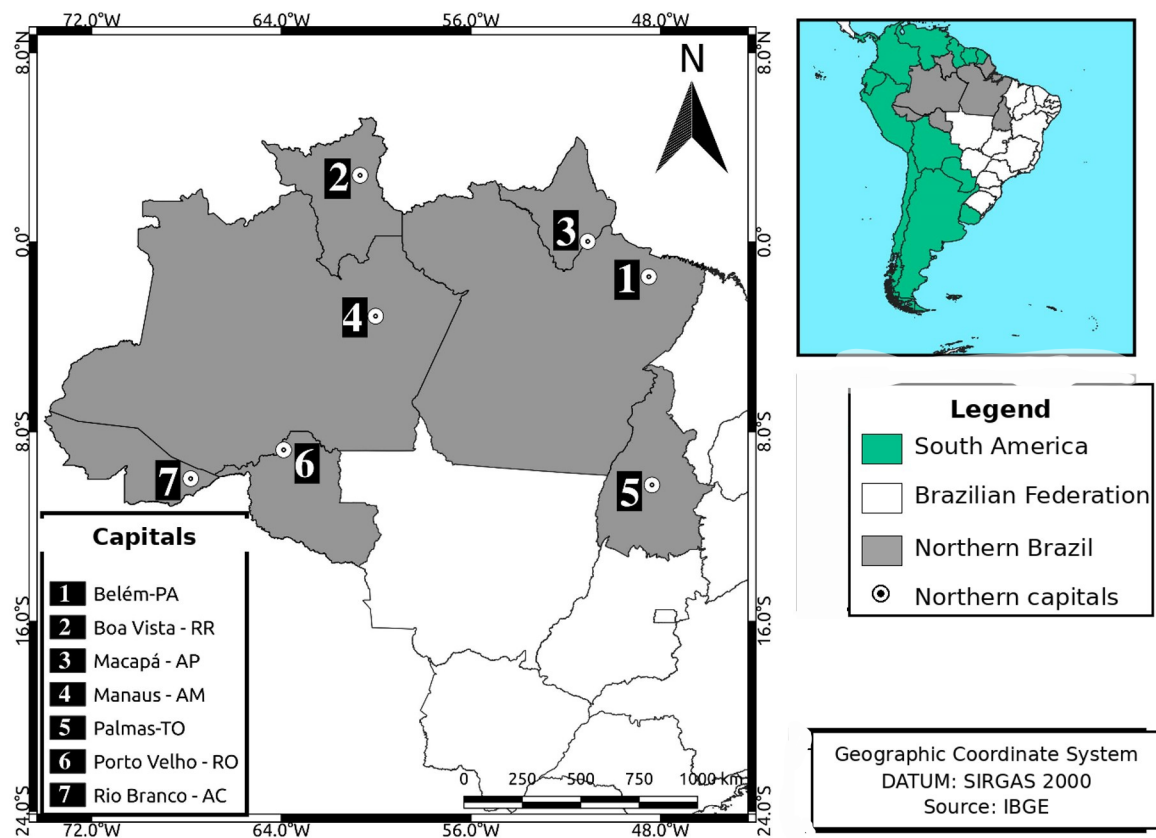


Figure 1. Geographic location of the capitals of Northern Brazil. Source: IBGE (2020), adapted by the authors, 2026.

2.2 Meteorological data and quality control

Daily maximum and minimum air temperature records were obtained from the Meteorological Database for Teaching and Research of the Brazilian National Institute of Meteorology (INMET) and from the Meteorology Network of the Brazilian Air Force Command (REDEMET). All stations follow World Meteorological Organization standards. Station codes and geographic information are shown in (Table 1).

The conventional weather station in Palmas began operating on October 8, 1993. Because heat-wave identification requires a long reference period, the Porto Nacional station was used to represent Palmas. Porto Nacional is located in the same mesoregion, approximately 60 km from Palmas, and both municipalities have similar climatic characteristics. According to the World Meteorological Organization, a surface weather station can represent an area of up to 200 km, supporting this substitution (WMO, 2008).

Measurement, storage, and transmission errors can occur even in official meteorological databases. Therefore, the data were first subjected to consistency analysis to identify anomalous records. Missing records were subsequently filled using Multiple Imputation by Chained Equations (MICE), a statistical procedure that generates conditional distributions from the observed dataset and produces multiple plausible imputations for missing values (van Buuren; Groothuis-Oudshoorn, 2011).

Table 1. Description of the meteorological stations used in the study.

Station	State	Code	Agency	Latitude (°)	Longitude (°)	Altitude (m)	Missing Tmax (%)	Missing Tmin (%)
1. Belém	PA	82191	INMET	-1.43	-48.43	10.0	2.3	0.7
2. Boa Vista	RR	82024	INMET	2.82	-60.66	83.0	19.0	16.8
3. Macapá	AP	82098	INMET	-0.05	-51.11	14.5	6.0	4.1
4. Manaus	AM	82331	INMET	-3.10	-60.01	61.2	4.5	4.1
5. Porto Nacional	TO	83064	INMET	-10.71	-48.41	239.2	17.3	14.0
6. Porto Velho	RO	82824	REDEMET	-8.70	-63.90	102.0	7.1	11.4
7. Rio Branco	AC	82915	INMET	-9.96	-67.80	160.0	18.5	11.7

Note: Tmax = daily maximum air temperature; Tmin = daily minimum air temperature. Source: Authors, 2026.

2.3 Heat-wave identification and intensity metrics

Heat-wave events were identified using the CTX90pct and CTN90pct indices. Following Perkins & Alexander (2013), the threshold for each calendar day was defined as the 90th percentile of the reference climatology (1980-2010), computed with a centered 15-day window. CTX90pct was calculated from daily maximum temperature, and CTN90pct from daily minimum temperature. A heat wave was defined as a period of at least three consecutive days with temperatures above the respective daily threshold.

$$\text{CTX90pct}_d = \text{P90} \{ T_{\max}(y,i), y = 1980, \dots, 2010; i = d - 7, \dots, d + 8 \} \quad (1)$$

$$\text{CTN90pct}_d = \text{P90} \{ T_{\min}(y,i), y = 1980, \dots, 2010; i = d - 7, \dots, d + 8 \} \quad (2)$$

where d is the calendar day, P90 is the 90th percentile, and $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum air temperatures for year y and day i , respectively.

Heat-wave intensity was evaluated using Exceedance Degree-Days (EDD), which expresses the accumulated amount, in degrees Celsius, by which temperature exceeded the climatological threshold during a heat-wave episode (Díaz et al., 2006).

$$\text{EDD} = \sum (T - T_{\text{clim}}), \text{ for } T > T_{\text{clim}}, \text{ from the first to the last day of the event} \quad (3)$$

$$\text{EDD} = 0, \text{ for } T < T_{\text{clim}} \quad (4)$$

where T is either maximum or minimum air temperature, according to the index used, and T_{clim} is the calendar-day 90th percentile for the reference period.

2.4 Descriptive analyses

Four main heat-wave characteristics were evaluated: (1) occurrence, defined as the number of heat-wave events; (2) annual frequency, defined as the number of days per year under heat-wave conditions; (3) duration, defined as the number of consecutive days in each event; and (4) intensity, expressed by EDD. The analyses were performed annually using descriptive statistics to summarize measures of position and dispersion (Wilks, 2011).

2.5 Trend analysis

To complement the descriptive analysis, temporal trends in annual heat-wave metrics were evaluated using the non-parametric Mann-Kendall test and Sen's slope estimator. The analysis was applied to the annual series of occurrence, frequency, and intensity for each capital and for the regional aggregated series from 1980 to 2018. The Mann-Kendall test was used to identify the presence and direction of monotonic trends, while Sen's slope was used to estimate the magnitude of the annual rate of change.

For occurrence and frequency, the regional series was calculated as the annual sum of heat-wave events and heat-wave days across the seven capitals, respectively. For intensity, the regional series was calculated as the annual mean intensity

among the capitals. City-scale analyses were also performed separately for each capital and for each heat-wave index, CTX90pct and CTN90pct.

A significance level of 5% was adopted. Positive and statistically significant trends were interpreted as evidence of increasing heat-wave occurrence, frequency, or intensity over time. In addition, simple linear regression was used as a complementary approach to evaluate the direction of change and the proportion of temporal variability explained by the year. The trend results were summarized using Mann-Kendall's tau, p-value, Sen's slope, and the coefficient of determination from the linear regression.

3. Results

3.1 Occurrence of heat-wave events

All capitals experienced heat waves in more than 40% of the years analyzed (Table 2). The highest percentages were generally observed for CTX90pct, indicating that daytime events were more frequent annually. CTX90pct identified 825 heat-wave events, with the largest numbers in Belém and Manaus, which together accounted for more than 35% of all daytime events. CTN90pct identified 806 events, with the largest number in Manaus.

The mean annual number of events represents the expected number of heat waves per year, whereas the standard deviation indicates interannual variability. At least one heat-wave event per year was expected in all capitals, and some cities had averages of more than three events per year. Belém, Macapá, Manaus, and Rio Branco had greater interannual variability than the remaining capitals.

Table 2. Occurrence of heat-wave events in the capitals of Northern Brazil from 1980 to 2018.

Capitals	Total events	Total events	Years with HW (%)	Years with HW (%)	Mean (SD) annual HW	Mean (SD) annual HW	Max. HW in one year	Max. HW in one year
	CTX90pct	CTN90pct	CTX90pct	CTN90pct	CTX90pct	CTN90pct	CTX90pct	CTN90pct
Belém	153	119	59.0	53.8	3.9 (5.9)	3.1 (5.9)	21	25
Boa Vista	129	110	59.0	51.3	3.3 (5.1)	2.8 (4.7)	20	20
Macapá	112	90	46.2	56.4	2.9 (5.1)	2.3 (3.5)	18	13
Manaus	142	164	64.1	41.0	3.6 (4.1)	4.2 (7.7)	15	28
Palmas	127	105	84.6	46.2	3.3 (3.8)	2.7 (4.2)	16	17
Porto Velho	63	87	64.1	46.2	1.6 (3.1)	2.2 (5.6)	18	25
Rio Branco	99	131	79.5	53.8	2.5 (3.3)	3.4 (5.2)	16	22

Note: SD = standard deviation; HW = heat wave. Source: Authors, 2026.

The annual behavior of occurrence is shown in (Figure 2). An increase in the number of heat-wave events was observed from the beginning of the 21st century onward. In Manaus, CTX90pct detected heat-wave occurrence in the last 18 years of the period, a pattern not observed in the other capitals. Years with higher event counts included 1984, 1998, 2005, 2010, 2015, and 2016, which coincide with years of high temperatures and drought episodes in Amazonia.

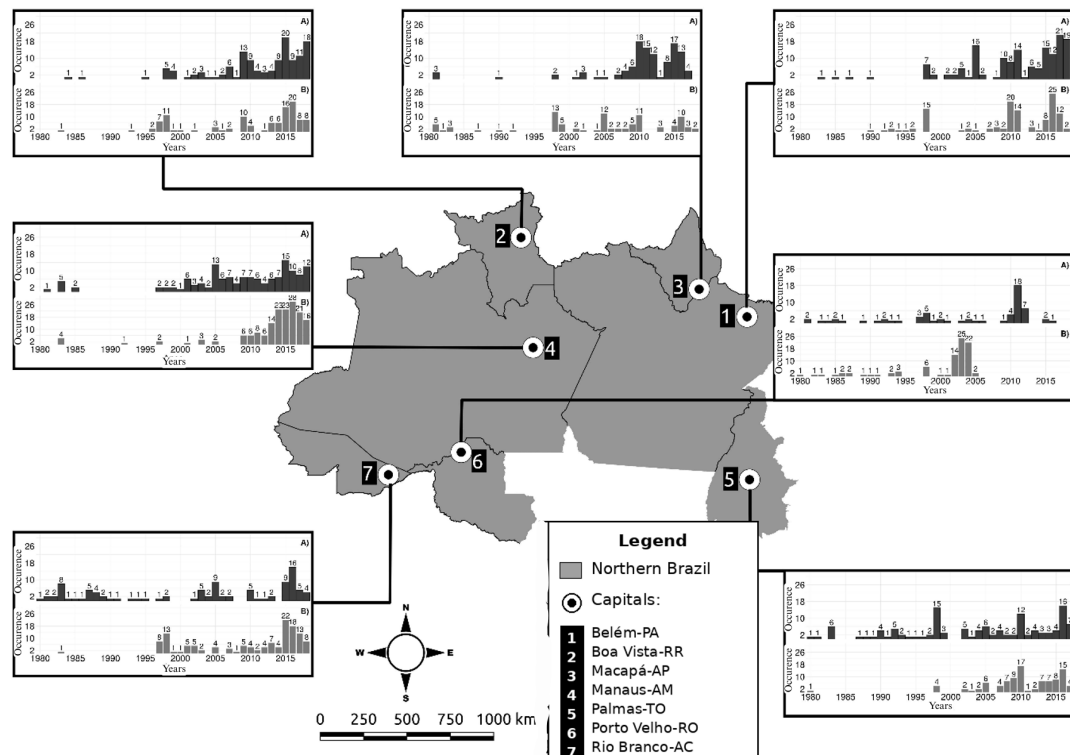


Figure 2. Annual occurrence of heat-wave events in the capitals of Northern Brazil from 1980 to 2018: (A) CTX90pct and (B) CTN90pct. Source: Authors, 2026.

3.2 Annual frequency

Annual frequency, expressed as the number of heat-wave days per year, was higher for CTX90pct in most capitals, except Manaus, Porto Velho, and Rio Branco (Table 3). This pattern indicates that the mean behavior of heat waves differed among the capitals and between daytime and nighttime indices. Standard deviations were high, exceeding 20 days in most cities, which indicates strong variability in annual frequency.

The maximum annual frequency was more than three times higher than the mean in all capitals and for both indices. For CTX90pct, the highest maximum frequencies were recorded in Macapá, Boa Vista, and Belém, the cities closest to the equator. For CTN90pct, Belém and Manaus showed the highest maximum frequencies, with years in which more than 40% of the annual days were classified as heat-wave days.

Table 3. Annual frequency of heat-wave events in the capitals of Northern Brazil from 1980 to 2018.

Capitals	Annual frequency (days)	Annual frequency (days)	SD of annual frequency (days)	SD of annual frequency (days)	Maximum annual frequency (days)	Maximum annual frequency (days)
	CTX90pct	CTN90pct	CTX90pct	CTN90pct	CTX90pct	CTN90pct
Belém	17.8	14.1	26.9	31.6	103	158
Boa Vista	16.1	12.0	27.0	22.0	116	100
Macapá	14.1	10.6	29.3	19.3	136	92
Manaus	16.4	20.3	20.0	39.4	83	153
Palmas	14.2	11.4	18.7	19.2	83	77
Porto Velho	6.0	9.5	12.6	25.4	69	109
Rio Branco	10.1	15.6	15.1	27.1	79	110

Note: SD = standard deviation. Source: Authors, 2026.

Figure 3 shows that the temporal behavior of frequency was similar to the pattern observed for occurrence. Except for Porto Velho under CTN90pct, the number of heat-wave days increased over time. CTX90pct showed the highest frequency values in the last decade of the study period in all capitals. For CTN90pct, an expressive increase was observed from 2009 onward, especially in Belém, Boa Vista, and Manaus.

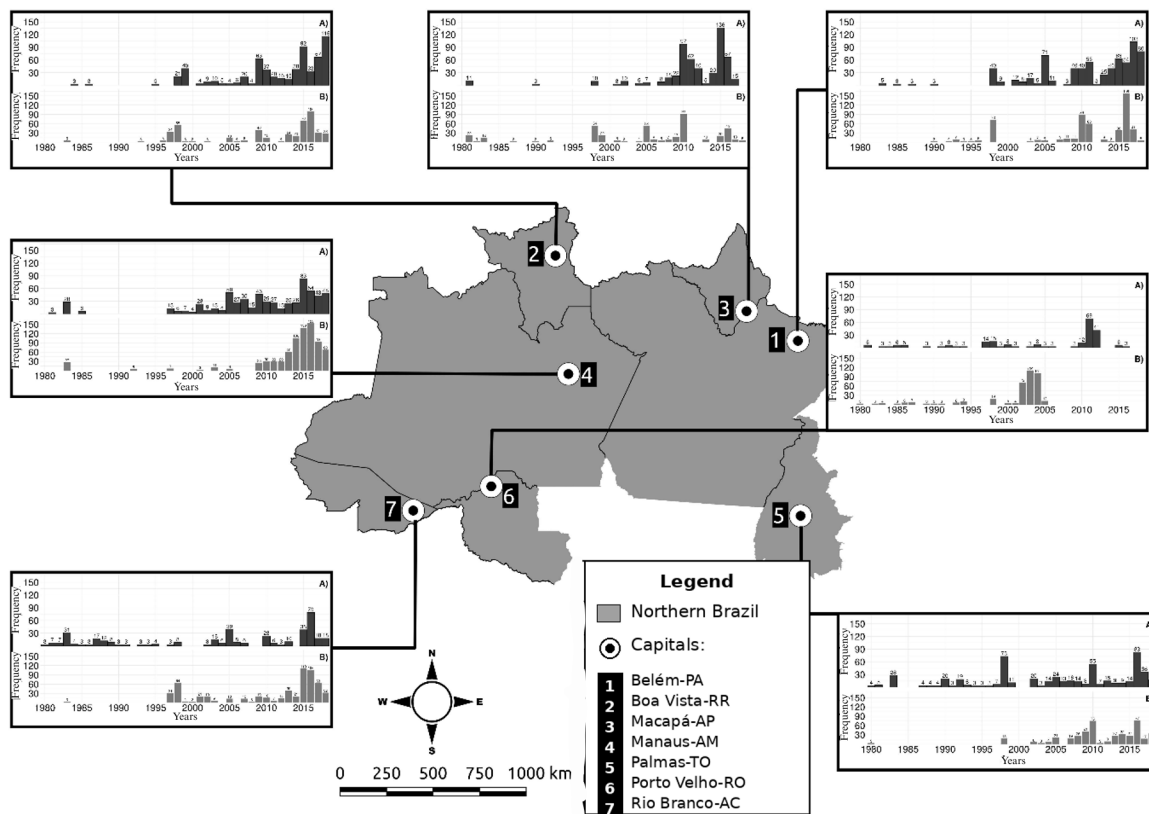


Figure 3. Annual frequency of heat-wave events, in days, in the capitals of Northern Brazil from 1980 to 2018: (A) CTX90pct and (B) CTN90pct. Source: Authors, 2026.

3.3 Duration

The duration characteristics of heat-wave events are summarized in (Table 4). CTX90pct showed an average duration of 4.4 days. Belém, Boa Vista, Macapá, and Manaus presented durations above this mean, and the highest values were observed in Boa Vista and Macapá. CTN90pct showed an average duration of 4.5 days, with all capitals presenting values above four days.

Events lasting three days were the most common in Macapá, Porto Velho, and Rio Branco for CTX90pct, whereas the other cities showed predominance of events lasting four to seven days. For CTN90pct, most cities had greater numbers of three-day events, although Manaus showed a substantial number of events lasting four to seven days. Events longer than seven days were less frequent for both indices.

Table 4. Duration of heat-wave events in the capitals of Northern Brazil from 1980 to 2018.

Capitals	Mean duration (days)	Mean duration (days)	3-day HW	3-day HW	4-7-day HW	4-7-day HW	>7-day HW	>7-day HW
	CTX90pct	CTN90pct	CTX90pct	CTN90pct	CTX90pct	CTN90pct	CTX90pct	CTN90pct
Belém	4.5	4.6	69	56	70	52	14	11
Boa Vista	4.9	4.2	56	57	59	46	14	7
Macapá	4.9	4.6	51	44	46	37	15	9
Manaus	4.5	4.8	62	65	71	82	9	17
Palmas	4.4	4.2	50	54	64	49	9	6
Porto Velho	3.7	4.3	46	42	14	38	3	7
Rio Branco	4.0	4.6	59	55	34	63	6	13

Note: HW = heat wave. Source: Authors, 2026.

Figure 4 presents duration histograms. For CTX90pct, all capitals except Porto Velho showed more than 50 events lasting three days, followed by a rapid decrease after five days. The longest CTX90pct event occurred in Boa Vista, beginning on September 14, 2018, and lasting 29 days. Manaus and Macapá also showed 20-day events, recorded in September and November 2015, respectively. For CTN90pct, most events were concentrated between three and five days, and the longest episode was observed in Macapá in February 2010, lasting 29 days.

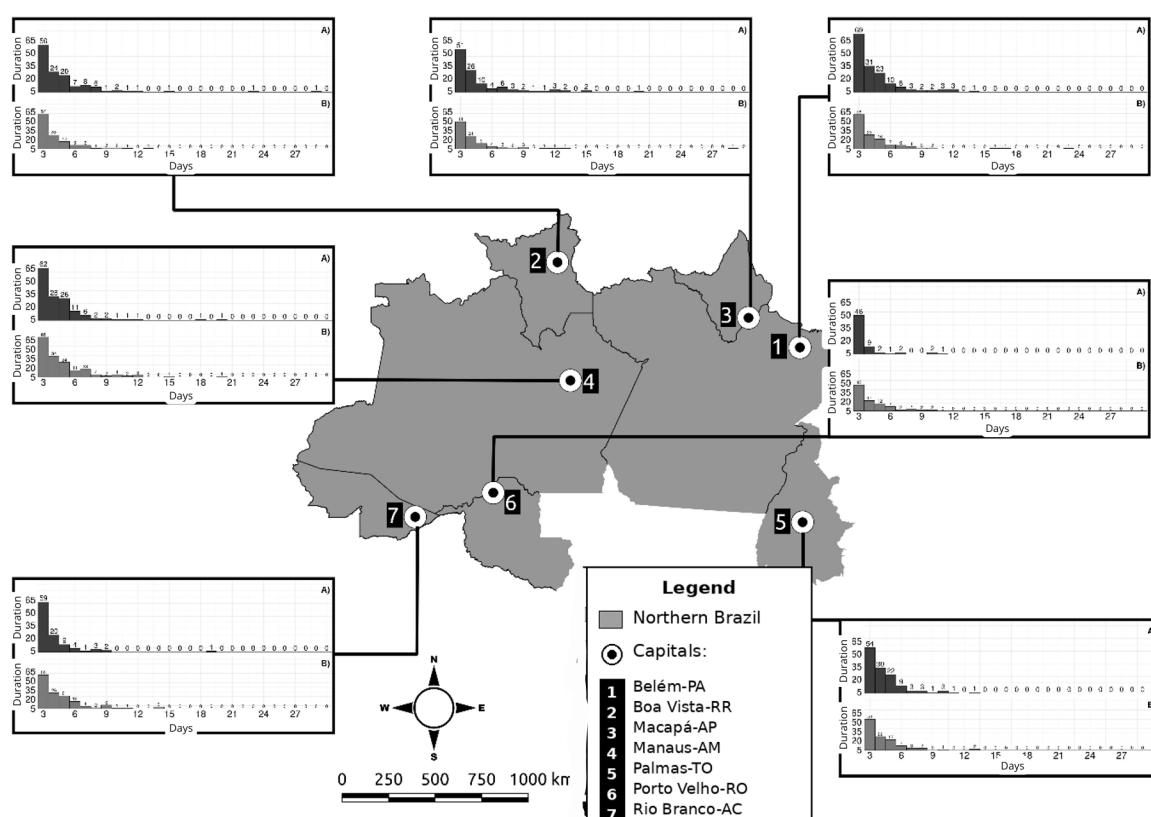


Figure 4. Duration histogram, in days, of heat-wave events in the capitals of Northern Brazil from 1980 to 2018: (A) CTX90pct and (B) CTN90pct. Source: Authors, 2026.

3.4 Intensity

Table 5 summarizes heat-wave intensity using EDD. For CTX90pct, all capitals showed annual mean intensity above 8 °C, with the highest values in Boa Vista and Palmas and the lowest values in Belém and Porto Velho. Although Manaus

had a high mean annual occurrence, the most intense daytime events were observed in other capitals. Boa Vista showed the highest standard deviation, indicating strong interannual variability in intensity.

For CTN90pct, the highest annual mean intensity occurred in Manaus (11.4 °C), which also showed the largest standard deviation. Rio Branco also presented EDD above 10 °C. Overall, CTX90pct events were more intense than CTN90pct events, indicating that daytime heat waves not only occurred more frequently in several capitals but also had a higher mean intensity.

Table 5. Annual mean intensity of heat-wave events in the capitals of Northern Brazil from 1980 to 2018.

Capitals	Annual mean intensity (°C)	Annual mean intensity (°C)	SD of annual intensity (°C)	SD of annual intensity (°C)	Maximum annual intensity (°C)	Maximum annual intensity (°C)
	CTX90pct	CTN90pct	CTX90pct	CTN90pct	CTX90pct	CTN90pct
Belém	8.9	6.1	2.7	1.8	16.3	10.6
Boa Vista	13.6	6.9	7.8	1.6	44.8	9.7
Macapá	9.6	6.6	3.5	2.0	16.3	13.1
Manaus	13.0	11.4	4.6	3.7	24.3	19.4
Palmas	14.6	9.8	5.0	2.2	32.1	14.9
Porto Velho	8.8	7.8	2.6	2.4	15.7	13.7
Rio Branco	11.7	10.6	3.4	3.3	22.8	16.5

Note: Intensity was calculated using Exceedance Degree-Days (EDD). SD = standard deviation. Source: Authors, 2026.

The annual behavior of EDD is shown in (Figure 5). For CTX90pct, the most expressive increase occurred in Boa Vista in 1999 and was not observed in the other capitals. Unlike occurrence and frequency, intensity did not show a clear increase in all cities, even in Belém and Manaus, where the annual number of heat waves increased. For CTN90pct, EDD values were lower than those observed for CTX90pct in all capitals, including the maximum values.

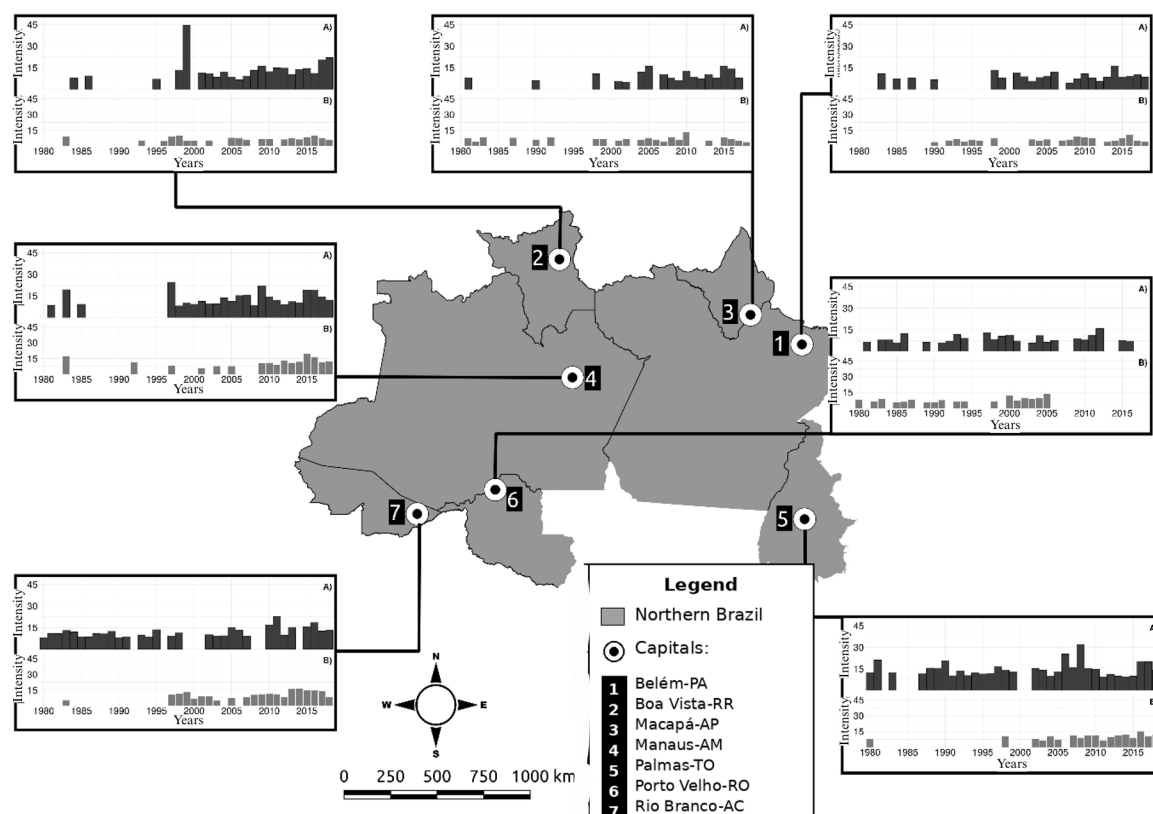


Figure 5. Annual mean intensity of heat-wave events in the capitals of Northern Brazil from 1980 to 2018: (A) CTX90pct and (B) CTN90pct. Source: Authors, 2026.

3.5 Trend analysis

Figure 6 summarizes the spatial distribution of significant trends in annual heat-wave metrics across the capitals of Northern Brazil. Overall, the results indicate a widespread increase in heat-wave occurrence, frequency, and intensity, although the magnitude and statistical significance of the trends varied among cities and between daytime and nighttime indices.

For CTX90pct, which represents daytime heat-wave events based on maximum temperature, significant positive trends were observed in Belém, Boa Vista, Macapá, Manaus, and Palmas for occurrence and frequency. Manaus showed the largest increase in annual frequency (+1.07 days year⁻¹), followed by Belém (+0.94 days year⁻¹) and Boa Vista (+0.83 days year⁻¹). Significant increases in intensity were also observed in Belém, Boa Vista, Macapá, and Manaus, with the strongest increase in Boa Vista (+0.50 EDD year⁻¹). In contrast, Porto Velho and Rio Branco did not show significant CTX90pct trends.

For CTN90pct, which represents nighttime heat-wave events based on minimum temperature, significant positive trends were more spatially widespread. Belém, Boa Vista, Macapá, Manaus, Palmas, and Rio Branco showed significant increases in occurrence and frequency. Manaus presented the highest increase in nighttime frequency (+0.92 days year⁻¹), followed by Rio Branco (+0.74 days year⁻¹) and Palmas (+0.61 days year⁻¹). Nighttime intensity also increased significantly in most capitals, especially in Rio Branco (+0.38 EDD year⁻¹), Palmas (+0.32 EDD year⁻¹), and Manaus (+0.29 EDD year⁻¹). Porto Velho was the only capital without significant increases for either CTX90pct or CTN90pct.

These results reinforce that the increase in heat-wave conditions in Northern Brazil was not spatially homogeneous. Belém, Boa Vista, Manaus, and Palmas showed consistent increases in several metrics, while Rio Branco presented a stronger signal for nighttime events. The absence of significant trends in Porto Velho suggests local differences in the temporal evolution of heat-wave characteristics. Overall, the spatial pattern indicates that both daytime and nighttime heat-wave conditions intensified in several capitals, with frequency showing the clearest and most consistent increase.

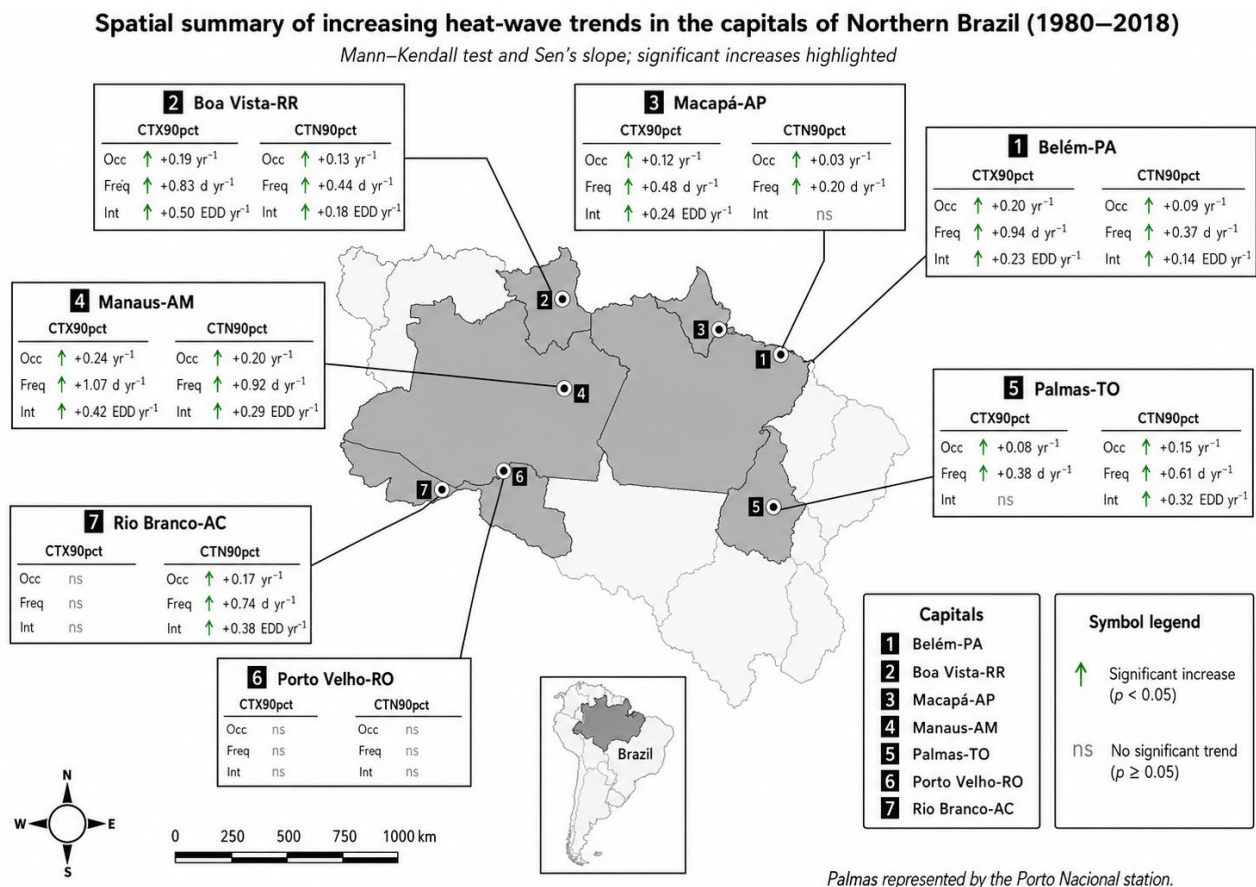


Figure 6. Spatial summary of significant trends in annual heat-wave occurrence, frequency, and intensity in the capitals of Northern Brazil from 1980 to 2018. Green arrows indicate statistically significant positive trends according to the Mann-Kendall test ($p < 0.05$), with Sen's slope values shown for each metric. "ns" indicates no significant trend. Occ = occurrence; Freq = frequency; Int = intensity; EDD = Exceedance Degree-Days. Palmas is represented by the Porto Nacional station. Source: Authors, 2026.

4. Discussion

The results showed that heat-wave occurrence, frequency, and intensity increased in several capitals of Northern Brazil between 1980 and 2018. This pattern was confirmed by the Mann-Kendall trend analysis, which indicated significant positive trends for both CTX90pct and CTN90pct at the regional scale. Therefore, the temporal evolution observed in the annual figures was not only descriptive but also statistically supported. The increase was particularly evident for frequency, indicating that the main temporal change was not only an increase in the number of heat-wave events, but also an expansion in the number of days under heat-wave conditions.

The increase in heat-wave metrics observed in this study is consistent with previous evidence for Brazil and South America. Bitencourt et al. (2020) identified an increase in heat-wave frequency across several Brazilian regions from 1961 to 2016, while Geirinhas et al. (2018) described key climatic and synoptic characteristics associated with heat waves in Brazil. At the continental scale, Feron et al. (2019) showed that heat waves in South America are expected to become more frequent, longer, and more intense under climate change. These findings are also consistent with the broader scientific understanding that warm extremes have increased in many regions and are projected to intensify under continued warming (Seneviratne et al., 2012; Perkins, 2015).

Belém and Manaus showed among the highest records for heat-wave occurrence and frequency, especially for CTX90pct and CTN90pct. These cities have the largest urban populations in Northern Brazil, and the interaction between regional warming and local urbanization may intensify thermal exposure. Previous studies have shown that urban areas can experience greater increases in heat stress than surrounding rural areas due to the urban heat island effect, changes in the surface energy balance, reduced vegetation cover, impervious surfaces, and reduced nocturnal cooling (Oleson et al., 2015; Wouters et al., 2017). Thus, the high frequency of events in Belém and Manaus may be related not only to regional climate variability but also to urbanization processes that amplify local heat exposure.

Some years with large numbers of heat-wave events coincided with major Amazon drought episodes, including 2005, 2010, and 2015/2016. These droughts were associated with anomalous sea surface temperature patterns in the tropical Atlantic and Pacific Oceans and with intense climatic anomalies in the Amazon Basin (Lewis et al., 2011; Jiménez-Muñoz et al., 2016). During drought periods, reduced cloudiness, lower soil moisture, and changes in the surface energy balance can lead to higher air temperatures and greater persistence of hot conditions. Therefore, the occurrence of heat waves in Northern Brazil may be influenced by both long-term warming and interannual climate variability associated with droughts, El Niño episodes, and tropical Atlantic variability.

The relationship between drought and heat waves is particularly relevant in the Amazon because compound climate extremes can intensify environmental and health impacts. Libonati et al. (2022) highlighted that the drought-heatwave nexus in Brazil has important consequences for fire occurrence and public health, especially in vulnerable regions. Silva Junior et al. (2019) also showed that Amazonian droughts can strongly influence fire responses, reinforcing the connection between heat, drought, vegetation stress, and fire risk. In this context, years with simultaneous drought and heat-wave activity may represent periods of increased climatic risk for Northern Brazil.

Frequency was one of the most important metrics in this study because it represents the number of days per year during which populations and ecosystems were exposed to heat-wave conditions. In several capitals, specific years saw more than 40% of days under heat-wave conditions, indicating prolonged exposure to anomalous heat. Prolonged exposure to extreme heat increases risks to human health, labor productivity, water demand, and energy consumption, and these impacts may be amplified in tropical regions, where high background temperatures occur year-round (Perkins, 2015; Mora et al., 2017). Recent evidence also indicates that human-perceived heatwaves are an escalating threat in Brazil, reinforcing the importance of considering exposure duration rather than event counts alone (Ballarin et al., 2024).

The duration results showed that heat waves in Northern Brazil generally lasted about four to five days, with fewer events exceeding seven days. This mean duration is like the values reported in national assessments for Brazil (Bitencourt et al., 2020). However, extreme events lasting 20 to 29 days were identified in Boa Vista, Macapá, and Manaus. Long-lasting events are particularly relevant because the impacts of heat waves tend to accumulate over time, especially when consecutive hot days are combined with insufficient nighttime cooling. This cumulative exposure may affect human thermoregulation, increase physiological stress, and intensify impacts on ecosystems and infrastructure (Perkins, 2015; Mora et al., 2017).

Intensity, as measured by EDD, was generally higher for CTX90pct than for CTN90pct, suggesting that daytime heat waves tended to produce larger exceedances above the climatological threshold. This result is consistent with the interpretation that extreme temperatures are strongly influenced by daytime radiative heating and surface-atmosphere interactions. Nevertheless, nighttime heat waves were also relevant, particularly in Manaus, Palmas, and Rio Branco. Nighttime heat can be especially harmful because it reduces nocturnal thermal recovery, which is important for human physiological adaptation during multi-day heat events. For this reason, the increase in CTN90pct should be considered an important signal for public-health risk assessment.

The use of both maximum and minimum temperature indices allowed the identification of daytime and nighttime heat-wave characteristics. This distinction is important because heat-wave impacts can vary by time of day and because nighttime heat stress may have different implications than daytime heat stress. Perkins and Alexander (2013) emphasized

the importance of using percentile-based indices to account for local climate conditions and to characterize different aspects of heat-wave behavior. In the present study, CTX90pct and CTN90pct showed both common and distinct patterns, indicating that daytime and nighttime heat extremes should be analyzed separately in tropical regions.

The spatial differences among the capitals demonstrate that heat-wave behavior is not homogeneous across Northern Brazil. Belém, Boa Vista, Manaus, and Palmas showed consistent increases in several metrics, whereas Porto Velho presented weaker or non-significant trends. Rio Branco showed a stronger signal for nighttime events than for daytime events. These differences may reflect the combined influence of regional climate variability, local geography, vegetation cover, urbanization, and land-use change. Therefore, the results support the need for local-scale monitoring and adaptation strategies rather than assuming a uniform heat-wave response across the entire Amazonian region.

The results also have practical implications for public policy. More persistent heat-wave days can affect public health, civil defense planning, electricity demand, water consumption, labor productivity, school activities, urban mobility, and fire risk. In Amazonian cities, where high humidity and elevated background temperatures are common, the perception of abnormal heat may be diminished, delaying protective responses among the population. Therefore, adaptation strategies should include heat-health warning systems, urban greening, improved housing ventilation, protection for outdoor workers, and integration between meteorological monitoring and health surveillance.

Overall, the findings highlight the importance of regional and local analyses of heat extremes in the Brazilian Amazon. The significant increase in heat-wave occurrence, frequency, and intensity indicates that heat exposure has intensified in recent decades across several capitals in Northern Brazil. These results reinforce the need for climate-risk communication, urban adaptation policies, and future studies integrating meteorological observations, gridded datasets, remote sensing, urbanization indicators, and health outcomes.

5. Limitations

This study has some limitations that should be considered when interpreting the results. First, the analysis was based on one meteorological station for each capital. Although these stations are official and follow standard observational procedures, a single station may not fully represent the spatial heterogeneity of urban areas, especially in large cities such as Manaus and Belém. Intra-urban differences associated with land use, vegetation cover, building density, and local ventilation patterns may influence the intensity and persistence of heat-wave conditions.

Second, missing temperature records were filled using multiple imputations. This procedure is appropriate for improving temporal continuity in long climate series, but it may introduce uncertainty, especially in stations with higher percentages of missing data. Therefore, the results should be interpreted as representative of the best available homogenized annual series rather than as an entirely gap-free observational record.

Third, the study used maximum and minimum air temperatures as the main variables for heat-wave identification. These variables are widely used in climate-extreme studies and allow the characterization of daytime and nighttime heat-wave events. However, heat stress also depends on other atmospheric variables, such as relative humidity, wind speed, and radiation. Therefore, future studies should incorporate thermal comfort indices, such as UTCI or apparent temperature, to better represent human heat stress in humid tropical environments.

Finally, this study did not include remote-sensing indicators, such as land surface temperature, vegetation indices, or urban expansion metrics. These variables could help explain intra-urban and intercity differences in heat-wave behavior, particularly in capitals affected by rapid urban growth, deforestation, or changes in land cover. The absence of explicit socioeconomic indicators also limited the assessment of population vulnerability and adaptive capacity.

6. Conclusions

The objective of this study was achieved by identifying and characterizing heat-wave events using the CTX90pct and CTN90pct indices. More than 800 heat-wave events were detected for each index from 1980 to 2018, with expressive interannual and spatial variability in occurrence, frequency, duration, and intensity.

Belém and Manaus had the largest numbers of events, suggesting that urbanization and urban heat island effects may contribute to heat wave behavior in the region. Most capitals showed an increase in heat-wave occurrence over time, especially from the beginning of the 21st century.

The results also showed that drought years were associated with more frequent heat-wave events, indicating that drought and heat extremes may be connected in Northern Brazil. This study contributes to understanding heat-wave behavior in a region where regionalized analyses remain scarce and highlights the need for further studies across different Amazonian cities.

Public policies and monitoring systems focused on extreme heat are essential to reduce the impacts of heat waves on health, ecosystems, infrastructure, and socioeconomic activities. Future studies should include additional stations, gridded datasets, urbanization indicators, and health outcomes to better quantify exposure and vulnerability in the Brazilian Amazon.

7. Authors' Contributions

Tiago Bentes Mandú: conceptualization, data curation, formal analysis, methodology, visualization, and writing – original draft. Márcia Sabrina Lima Aguiar: supervision, methodology, validation, and writing – review and editing. Eduardo Almeida da Silva: data organization, validation, formal analysis support, and writing – review and editing. Ana Carla dos Santos Gomes: supervision, literature review, interpretation of results, and writing – review and editing. All authors read and approved the final version of the manuscript.

8. Conflicts of Interest

The authors declare no conflicts of interest.

9. Ethics Approval

Not applicable.

10. Artificial Intelligence Statement: Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to support English translation, language editing, and formatting according to the target journal template. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the manuscript.

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