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Long-term trends in heatwave in the São Paulo megacity using the excess heat factor

Tendências de longo prazo de ondas de calor na megacidade de São Paulo usando o fator de calor excessivo

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ABSTRACT

Extreme weather events have been reported more frequently, with heatwaves being responsible for thousands of deaths around the world every year. The Excess Heat Factor (EHF) is an indicator developed to identify and classify heatwaves according to their severity, based on two indices, significance and acclimatization, which refer to how hot a three-day period was in relation to a historical reference and the past thirty days, respectively. Adaptable for each region, the EHF allows the separation of events into moderate, severe, and extreme. This metric was used in the present study to identify and characterize heatwaves in the megacity of São Paulo between 1936 and 2023. The historical reference was defined as 1961-1990, the official normal period defined by the World Meteorological Organization (WMO). The results showed that approximately 75% of the severe or extreme events occurred during summer, revealing that severe and extreme heatwaves are not restricted to the typical warmest season. According to the EHF metrics, the city of São Paulo experienced 84 severe heatwave events, with some lasting over 20 days. Only 4 extreme events were registered: one in 1972, one in 2020, and two in 2023. The November 2023 extreme heatwave was the strongest ever registered in São Paulo. Positive and significant (p=0.05) historical trends were found for the number of heatwave events and also for maximum severity and the duration of the events, and as a consequence for the thermal load, especially after the 1970s.

Keywords: extreme temperature events; urban climate variability; thermal stress; climate change impacts; temperature extremes; historical climate analysis.

RESUMO

Eventos climáticos extremos têm sido relatados com maior frequência, sendo as ondas de calor responsáveis por milhares de mortes ao redor do mundo todos os anos. O fator de calor excessivo (EHF, do termo em inglês *Excess Heat Factor*) é um indicador desenvolvido para identificar e classificar ondas de calor de acordo com sua severidade, com base em dois índices: significância e aclimatação. Eles se referem a quão quente foi um período de três dias em relação a uma referência histórica e aos últimos 30 dias, respectivamente. Adaptável para cada região, o EHF permite a separação dos eventos em moderados, severos e extremos. Essa métrica foi utilizada no presente estudo para identificar e caracterizar ondas de calor na megacidade de São Paulo entre 1936 e 2023. O período de referência histórica foi baseado no intervalo de 1961 a 1990, considerado o período normal oficial definido pela Organização Meteorológica Mundial (OMM). Os resultados mostraram que aproximadamente 75% dos eventos severos ou extremos ocorreram durante o verão, revelando que ondas de calor severas e extremas não se restringem à estação tipicamente mais quente. De acordo com as métricas do EHF, a cidade de São Paulo registrou 84 eventos de ondas de calor severas, algumas delas durando mais de 20 dias. Apenas quatro eventos extremos foram registrados: um em 1972, um em 2020 e dois em 2023. A onda de calor extrema de novembro de 2023 foi a mais intensa já registrada em São Paulo. Tendências históricas positivas e significativas (p=0,05) foram identificadas para o número de eventos de onda de calor, bem como para a severidade máxima e a duração dos eventos e, consequentemente, para a carga térmica, especialmente após a década de 1970.

Palavras-chave: eventos extremos de temperatura; variabilidade climática urbana; estresse térmico; impactos das mudanças climáticas; extremos de temperatura; análise climática histórica.

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Introduction

Extreme weather events have been reported with increasing frequency in recent decades, with heatwaves representing one of the most impactful hazards to human health and urban systems worldwide (Liu et al., 2020; Hundessa et al., 2025; Matthews et al., 2025), particularly affecting vulnerable populations (Díaz et al., 2001; McGeehin and Mirabelli, 2001; Gouveia et al., 2003; Fouillet et al., 2008). Rising global temperatures have contributed to an increase in both the frequency and intensity of extreme heat events, and projections indicate that these trends are likely to continue throughout the twenty-first century (Meehl and Tebaldi, 2004; Guo et al., 2018; Lamb et al., 2021; Perkins-Kirkpatrick and Lewis, 2022). Consequently, heatwaves have become responsible for thousands of deaths every year across different regions of the world, particularly in densely populated urban areas (Robine et al., 2008; Gao et al., 2026). Recent studies also indicate that the exposure of the population to extreme heat has increased substantially in recent decades due to the combined effects of climate change and urban expansion (Chen et al., 2023).

Urbanization processes further intensify the impacts of extreme heat (United Nations Human Settlements Programme, 2022; Gao et al, 2024). Large cities tend to experience higher temperatures than surrounding rural areas due to the urban heat island effect, which is associated with land-use changes, reduced vegetation cover, and high concentrations of built-up areas. In addition, demographic and socioeconomic factors, such as population aging and social vulnerability, can increase sensitivity to extreme heat events, particularly among children and elderly populations (World Health Organization, 2015; Wondmagegn et al., 2021; Zhou, Q.-Y. et al., 2025). Furthermore, recent research indicates that a substantial fraction of current heat-related mortality can already be attributed to anthropogenic climate change (Vicedo-Cabrera et al., 2021). Therefore, long term and continuous monitoring of heatwaves occurrence have been central to provide the needed basis to perform attribution and to drive policies toward the mitigation of heatwave impacts, especially in urban areas, where the exposure of the population is high and heatwave intensity is amplified (Gao et al., 2024). In order to monitor and characterize heatwave events, several indices have been developed based on climatological thresholds and temperature anomalies, reflecting the growing need to better quantify the frequency, duration, and intensity of extreme heat events under a warming climate (Saxena et al., 2024). Different methods can be used to define the threshold, where the exceedance of a maximum temperature threshold on a given day is the most straightforward. The Bureau of Meteorology of Australia uses a fixed threshold of 35°C for five consecutive days or 40°C for three consecutive days. Portugal meteorological service defines heat waves as periods of at least six consecutive days in which the maximum temperature is 5°C higher than the daily average. Brazil meteorological institute (INMET) uses a similar threshold for temperature but considers at least five consecutive days. Other definitions of heatwaves have been proposed depending on regional climate characteristics (Rohini et al., 2016; You et al., 2017; Reis et al., 2019; Tolika, 2019; Varghese et al., 2019).

Heatwaves defined only by daily maximum temperature anomalies have been shown not to fully capture the impacts on human health. Previous research indicated the importance of considering thermal load metrics that also consider heat accumulation overnight (Pattenden et al., 2003; Nicholls et al., 2008), following a very hot day. A low dissipation of heat overnight will certainly result in an excess heat, which would be captured by the daily mean temperature (Nairn and Fawcett, 2014). On this basis, Nairn and Fawcett (2014) proposed an alternative index named excess heat factor (EHF), which is based on three-day-averaged daily mean temperature. Additionally, they have also included an acclimatization term that measures the three-day-averaged daily mean temperature difference to the average temperature of the preceding 30 days, which measures heat stress as a short-term anomaly. This is based on the principle that biological systems struggle to cope with a sudden rise in temperature (Nairn and Fawcett, 2013).

Therefore, EHF combines two components, a significance index, which compares a three-day average temperature with a historical threshold, and an acclimatization index, which considers temperature conditions during the previous thirty days. This approach allows for the identification and classification of heatwaves into different levels of severity, including moderate, severe, and extreme events (Nairn et al., 2018).

The Excess Heat Factor (EHF) has been widely used, and it has been shown to be well-suited to characterize heatwave hazards due to its ability to incorporate both the long-term climatological context and short-term acclimatization conditions (Nairn and Fawcett, 2014; Loridan et al., 2016; Oliveira et al., 2022; Jangi et al., 2024; Fernandez-Medina et al., 2025).

Although heatwave studies have expanded globally, regional and city-scale analyses remain essential, especially in rapidly growing urban areas in the Global South. Advanced understanding of the characteristics and historical evolution of heatwave events in large metropolitan regions can provide valuable information for climate risk assessment and urban resilience planning.

In this context, the present study aims to identify and characterize heatwave events trend in the city of São Paulo using the innovative approach of Excess Heat Factor (EHF). The analysis covers the period from 1936 to 2023 and adopts the climatological reference period of 1961–1990, defined by the World Meteorological Organization. By examining the frequency, duration, severity, and temporal trends of heatwave events, this study aims to contribute to the understanding of extreme heat behavior in one of the largest urban areas in South America.

Materials and Methods

São Paulo Metropolitan Region

The study area, the city of São Paulo-SP, is located in the São Paulo Metropolitan Region (RMSP) and is part of the southeastern region of Brazil (Figure 1). It is estimated that about 60.12% of its area is urbanized (IBGE, 2019). The municipality has approximately 11,451,245 inhabitants, with the majority in the age range of 25 to 29 years (IBGE, 2022). However, the number of elderly individuals has been increasing throughout the state of São Paulo (SEADE, 2022). As noted by Diniz et al. (2020), the higher mortality of elderly people during heatwaves in RMSP is related to cardiovascular and respiratory diseases, particularly on days with higher maximum temperatures. Moreover, projections for the coming decades, considering the Representative Concentration Pathways (RCPs) shown in the fifth IPCC report (IPCC, 2023), indicate increased future risks.

Data acquisition

São Paulo has one of the oldest and most consistent meteorological data monitoring systems in the state. Daily average, minimum, and

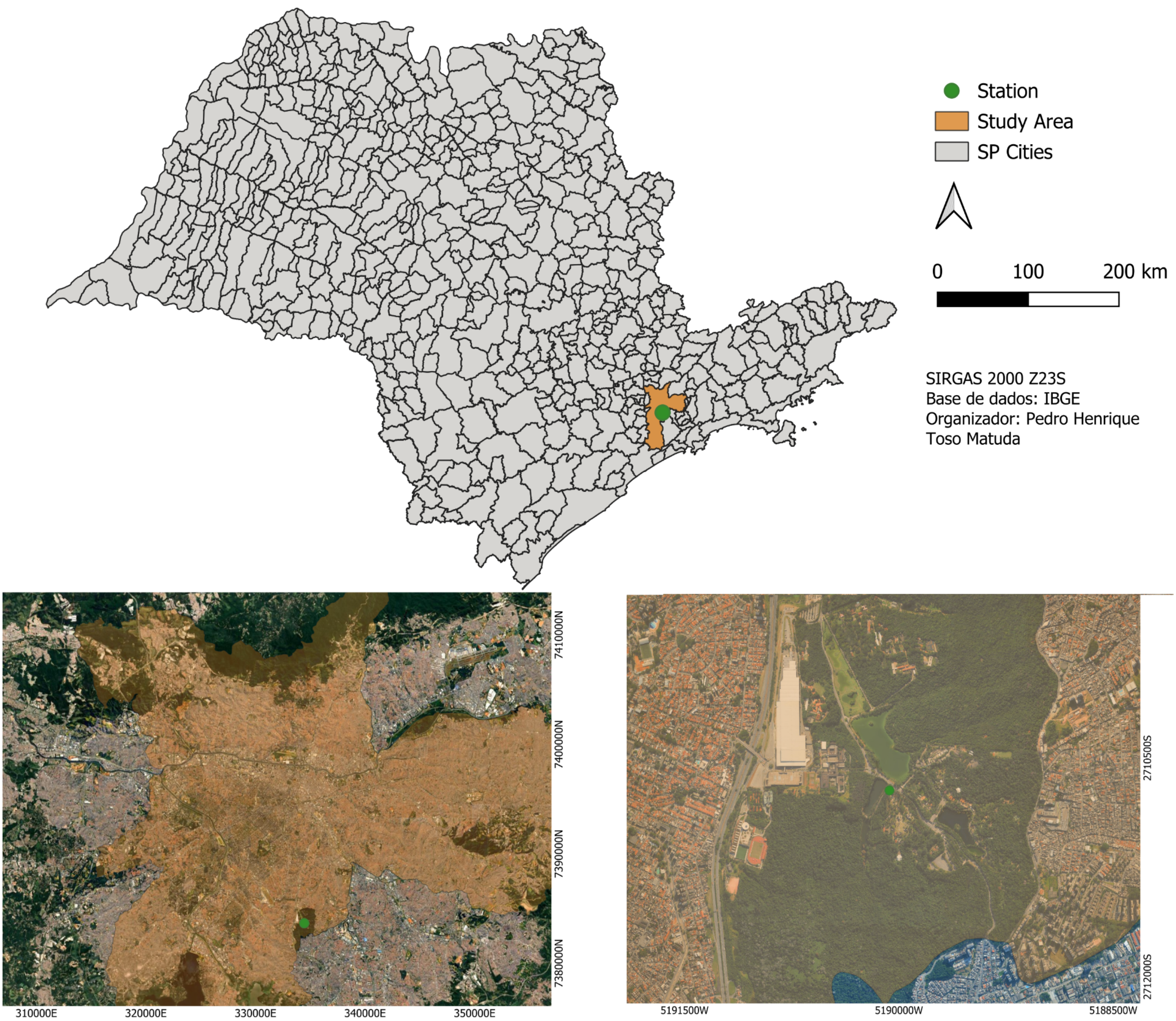

Figure 1 – Location of the Meteorological Station of the Institute of Astronomy, Geophysics, and Atmospheric Sciences at the University of São Paulo within the context of the City of São Paulo.

maximum temperature data for the analyzed period were provided by the Meteorological Station of the Institute of Astronomy, Geophysics, and Atmospheric Sciences at the University of São Paulo (EM IAG-USP, http://www.estacao.iag.usp.br/), located at Av. Miguel Estéfano, 4200 - Água Funda, located in the southern part of the city, in a more vegetated area (Figure 1, created using the QGIS software). The EHF calculation method requires at least 30 years of data to establish climatological references, which is also consistent with the objective of analyzing climatic trends, according to the World Meteorological Organization (INMET, 2022). The data also included records from the Mirante de Santana station, located in the northern part of the city. Although it was not used in the present study, it may be included in future research to provide a better understanding of spatial differences within the city. We acknowledge that the EM IAG-USP station does not fully represent the most urbanized areas of São Paulo, where heatwave intensity is typically higher. However, due to its location in a green area, it provides a useful baseline reference.

Excess heat factor

The EHF is obtained from the product of two indices (Nairn and Fawcett, 2014): the significance index (EHIsig) and the acclimatization index (EHIaccl). The first is a measure of how hot the average temperature was over a three-day period relative to the 95th percentile of the local historical average temperature series (T95). If the average daily temperature over the three days (Ti+Ti1+Ti2) exceeds the 95th percentile within the climatological series of daily temperature for the region, a heatwave event is considered to have occurred (Equation 1).

The second index, the acclimatization index, measures how hot a three-day period is in relation to the recent past, specifically the last thirty days ((Ti+...Ti30)/30) (Equation 2). This inclusion assumes that, while people may be acclimatized to long-term local climatic conditions, this may not hold true for abrupt temperature variations. The human body takes time to adjust to sudden temperature changes (Nairn and Fawcett, 2014). If EHIaccl is positive, then the average temperature over the three days is warmer than the average temperature of the recent past; consequently, there may be difficulties in acclimatization, which can lead to health problems. Both indices can be thought of as anomalies, the first relative to climatology and the second relative to the recent past, thus can be expressed in terms of units of temperature (°C). The adoption of periods results in events having a moving window of three days.

If EHIsig is positive, then a heatwave is considered to have occurred during the evaluated period, and an EHIaccl greater than 1.0 is an aggravating factor, which increases the EHF. Therefore, the combination of these two indicators (Equation 3) explains why the unit of the EHF is °C².

$$EHIsig = \left(\frac{Ti + Ti1 + Ti2}{3}\right) - T95 \tag{1}$$

$$EHIaccl = \left(\frac{Ti + Ti1 + Ti2}{3}\right) - \left(\frac{Ti+\ldots Ti30}{30}\right) \tag{2}$$

$$EHF = max(0, EHIsig) \times max(1, EHIaccl) \tag{3}$$

The EHF value refers to intensity, and for classifying the severity of a heatwave, Nairn and Fawcett establish the 85th percentile of EHF (hereinafter referred to as EHF85) as the threshold to separate moderate events from severe ones, considering all positive EHF values from the local historical series. This is based on the principle that each severity threshold varies from region to region, given people's acclimatization to the prevailing conditions in their area. As shown in Table 1, to characterize those heatwave events as extreme, it is recommended to use the threshold EHF≥3 × EHF85. Therefore, every time that an EHF value exceeds 3 times the EHF85 it is considered an extreme heatwave event.

Additionally, the Heat Event Moments (HEM), which can be in °C² or dimensionless (after severity has been calculated), describe other characteristics of the heatwave event: peak, which is the maximum recorded temperature during the event; load, which is the sum of the severity values during a heatwave event; length, which counts the continuous days of the event; and mean, calculated as the ratio of load to length.

Statistical analysis

The Mann-Kendall test is widely used in climatological time series analysis (Wilks, 1995), which tests the null hypothesis that there is no trend in the data, returning whether there is a monotonic trend (without significant fluctuations), either positive or negative, or if none exists. This test holds the advantage over parametric tests of being less influenced by outliers (Silva et al., 2022). The following equation (Equation 4) is presented, where xi and xj are values at times i and j, with results S being positive or negative, indicating upward or downward trends, respectively.

$$S = \sum_{i=1}^{n-1} \sum_{j=1}^{n} sgn(x_j - x_i) \tag{4}$$

In which: sgn(Xi - Xj):
1, if (Xi - Xj)>0;
0, if (Xi - Xj)=0;
-1, if (Xi - Xj)<0.

Table 1 – Classification of EHF severity as a function of EHF intervals taking percentile 85 of EHF (EHF85) as reference.

Base EHF	Severity
EHF<EHF85	Moderate (≤1,0)
EHF85≤EHF<3*EHF85	Severe (>1,0 and ≤3,0)
3*EHF85≤EHF	Extreme (>3,0)

Source: Adapted from Nairn et al. (2018).

In the absence of a trend, S is a random variable represented by the following equation (Equation 5), returning a Z value and a p-value (if the latter is ≤0.05). In this case, the null hypothesis is rejected, concluding that there is a significant non-monotonic trend.

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

$Z = \frac{S-1}{\sqrt{(S)}}$, if S > 0

0, if S = 0

$\frac{S+1}{\sqrt{(S)}}$, if S < 0

Results and Discussion

The following sections present the main findings regarding the frequency, seasonality, and temporal trends of heatwaves, as well as the historical evolution of their critical moments based on the Excess Heat Factor (EHF) over an extensive period of 88 years. These results are discussed in the context of global climate change and compared with other related studies, providing insights into the current and possible future scenarios for the city of São Paulo.

Figure 2 presents a graphical illustration of the T95 of daily average temperatures used in the EHF calculations and the 85th percentile (EHF85=4.66°C²) of the positive EHF values, which separates moderate (lower) from severe (equal to or greater than) values, while values greater than or equal to 3*EHF85=13.98°C² are classified as extreme. The daily average temperature in São Paulo had its highest frequency between 18 and 20°C. Meanwhile, the EHF data show a higher frequency in the moderate category, as indicated by the thresholds of different severities, with the EHF range between 0 and 2°C² being the most frequent (51% of EHF events). Although low and moderate events account for more than 80% of the days with excessive heat, severe days exceed 10%, which raises a warning for the future, as they are becoming increasingly frequent.

Figure 3 illustrates the seasonal distribution of EHF events for all severity categories. A rise in heatwave occurrences can be observed in September, continuing until April, with the highest frequency of excessive heat events occurring during the summer months, especially in January, which had the most occurrences. August showed the lowest

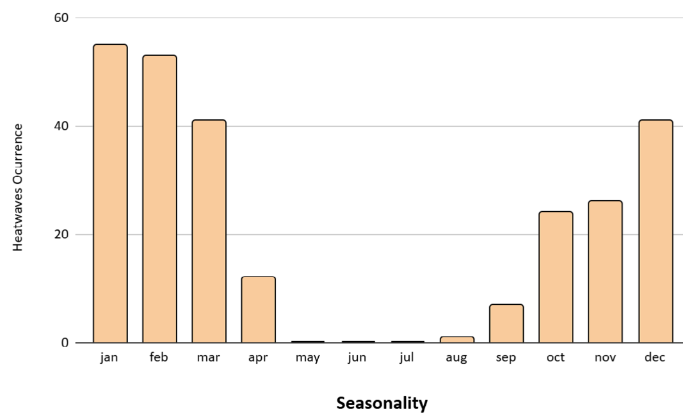

Figure 3 – Monthly (seasonal) distribution of EHF events occurrence in São Paulo from 1936 to 2023.

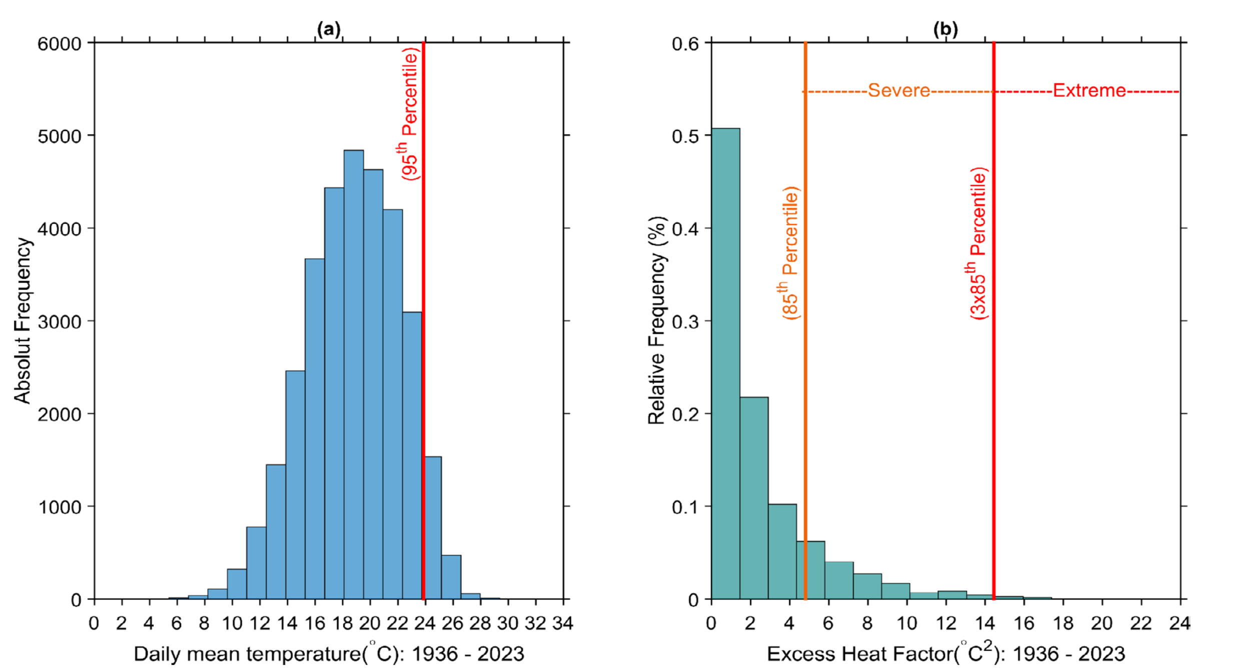

Figure 2 – (a) Distribution of the absolute frequency of daily average temperature in São Paulo for the period from 1936 to 2023 with the identification of T95=23.86°C (red line). (b) Distribution of the frequency of EHF values, accompanied by severe threshold based on EHF85=4.66°C² (orange line) and the extreme threshold (red line), which is three times the severe line.

frequency, with events occurring only in 2023. Meanwhile, 36% of the excessive heat days recorded in September occurred in that same year, highlighting how atypical this period was. In May, June, and July, São Paulo did not experience any excessive heat days. There is a greater prevalence of excess heat events during summer, representing more than 60% of the occurrences.

Figure 4 displays histograms of the maximum severity, length of events, peak and load, highlighting severe and extreme cases. It illustrates how the most severe case was entirely atypical, even when considering severe and extreme events. It also demonstrates that regardless of the severity of an event, the length can vary between less than five days and over ten days. However, for both characteristics, the most common events last fewer than five days and with a severity below one (moderate). Among the severe and extreme events in Sao Paulo, length and loading variability is significant, revealing the diversity in these heatwave categories. The comparison between the impact of short and acute heatwaves against the impacts of long and less acute heatwaves is still a matter of evaluation, and each case certainly requires a different policy approach. A major matter of concern is that positive trends were observed for both length and load of these heatwave categories in São Paulo (Figures 5 and 6), indicating the likelihood of a compound effect between intensity and duration of heatwaves in the city.

Figure 5 shows the historical evolution of the frequency of excessive heat days by severity category in São Paulo over the decades. The graph indicates a clear increase in the frequency of heatwaves from the 1970s onward, with a positive trend statistically significant (p=0.00609), a pattern also observed in other regions experiencing rapid warming and urban expansion (Wen et al., 2024). A dip in the frequency only occurred in the 2000s, before an intense increase. In total, 84 severe events and 4 extreme events were identified.

In the previous decades, 10 days of excessive heat per year were a rare occurrence, and there were even years with no such events. Starting in 1968, every year recorded positive EHF occurrences. The number of excessive heat days nearly doubled in the 1970s compared to the 1960s.

Among the notable years, 2023 recorded the highest frequency of excessive heat days, with a total of 104 days, with records across the entire southeast of Brazil. Using the excess heat factor (EHF), Fernandez-Medina et al. (2025) was able to determine the excess mortality associated with the November 2023 extreme heat wave in Rio de Janeiro, Brazil, when temperatures reached 42°C.

The longest severe event lasted 24 days and occurred in January 2014. The prolonged duration of this event suggests that persistence, rather than intensity alone, may play a key role in its impacts. This period has been associated with increased mortality in São Paulo, as reported in municipal health reports based on data from the PRO-AIM system and mortality estimates from the SEADE Foundation (Santos et al., 2014). Although not all excess deaths can be directly attributed to heat exposure due to natural variability in mortality rates, these findings reinforce the importance of prolonged heatwaves as a public health concern, especially when combined with additional stressors such as low relative humidity. Overall, these results highlight the relevance of considering cumulative heat exposure when assessing the impacts of extreme heat events. Similar associations between heatwave events and increased mortality have been reported in several regions worldwide (Odunmorayo et al., 2025). New technologies for identifying urban heatwaves have been shown to improve the mitigation of

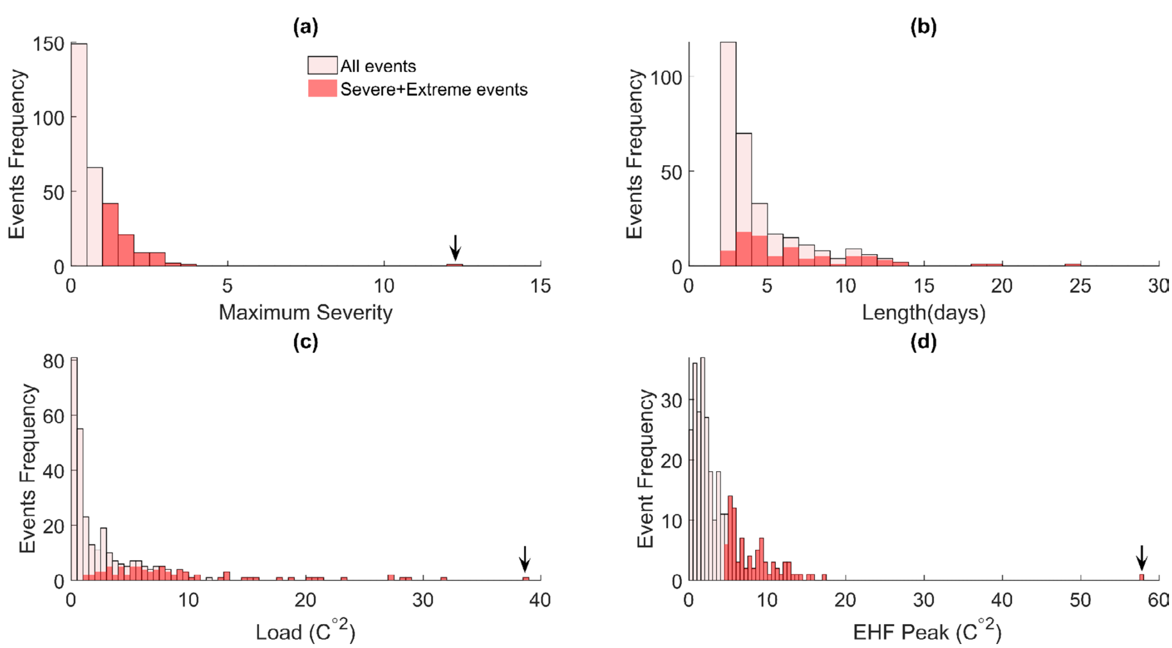

Figure 4 – Histogram of the EHF moments: (a) maximum severity, (b) event length in days, (c) load, and (d) peak, with extreme events indicated by an arrow.

these impacts. The use of social media and deep learning to detect the most vulnerable areas and monitor population behavior during heatwave events is an example, as demonstrated by Soomro et al. (2025). Adopting these technological approaches, this method accurately identified 86% of the officially recorded heat hotspots in southeastern Pakistan, although further refinement is still required.

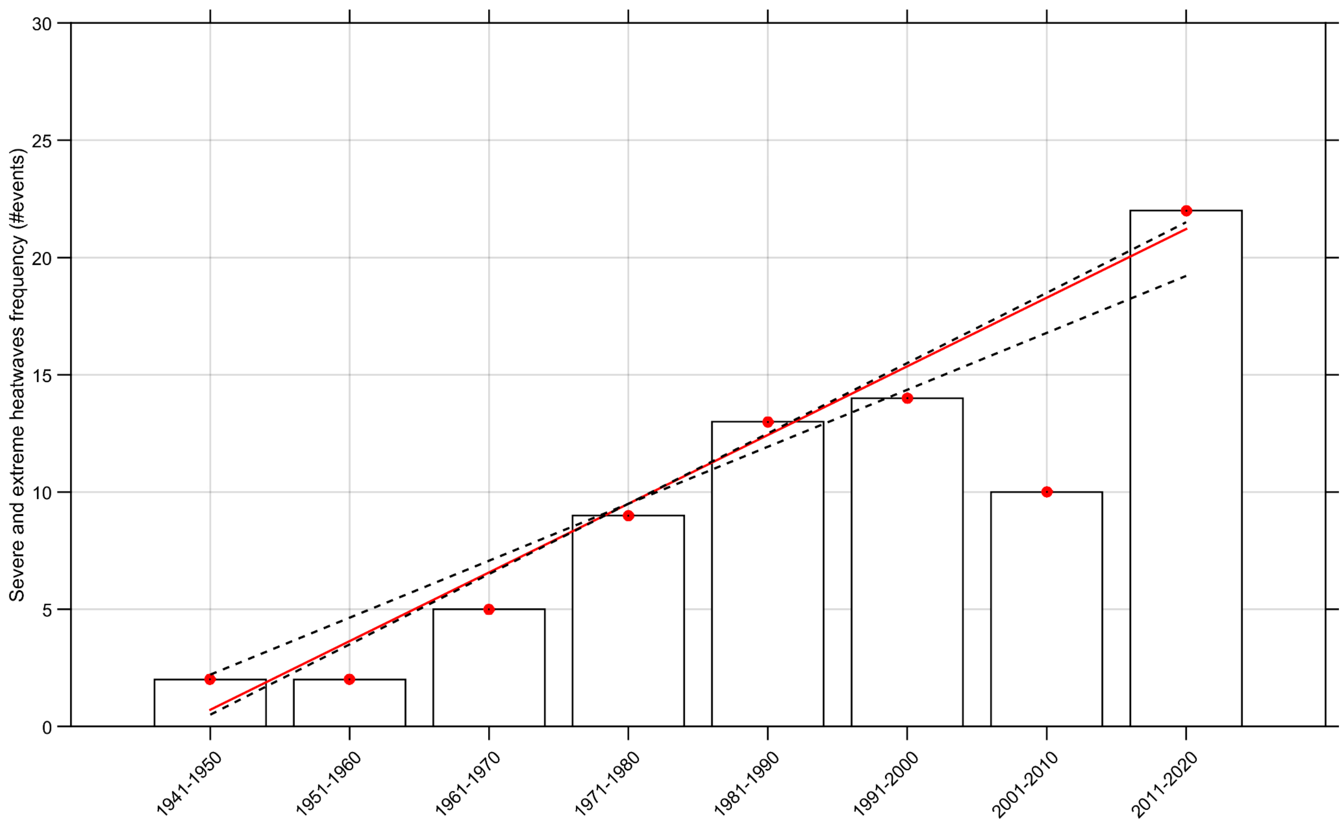

Figure 5 – Decadal trend in severe and extreme heatwave frequency in the city of São Paulo.

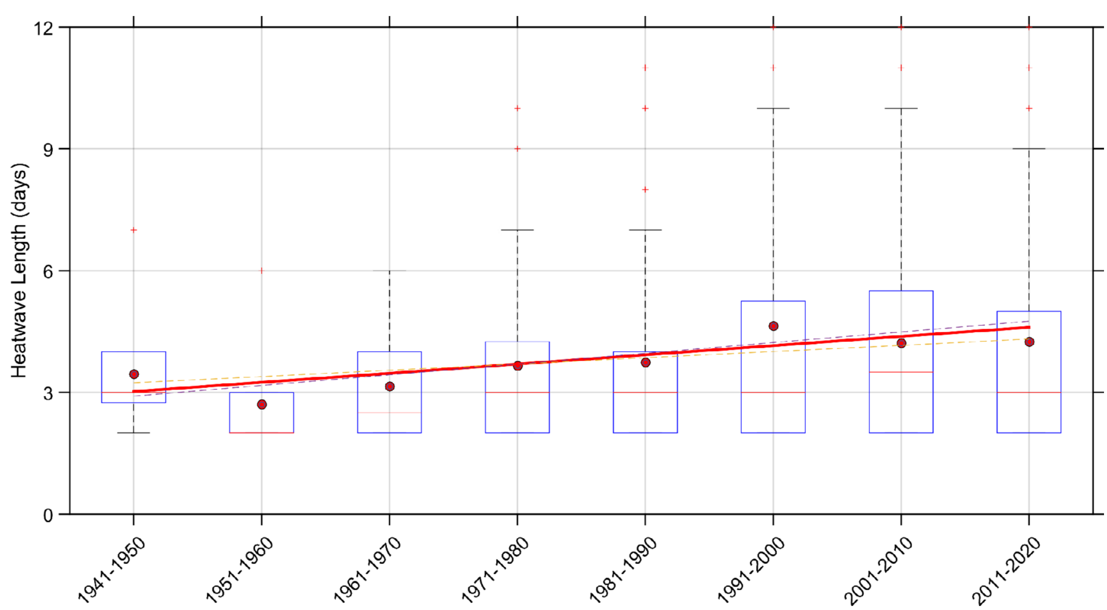

Figure 6 – Decadal trend in heatwave length in the city of São Paulo.

Figure 6 shows the decadal evolution of the duration of excessive heat events. Regarding the decadal average, a positive trend with statistical significance was identified (p=0.0061). The boxplot reveals an increase in the 3rd quartile between the 1960s and 2020, indicating that the duration of excessive heat events lasting 4 to 5 days has become more common in recent decades. As these events become increasingly prolonged, they tend to produce greater cumulative thermal stress, particularly in large urban areas where built surfaces can intensify heat retention (Jangi et al., 2024), it is expected that they will present a greater load, which is supported by the decadal evolution of the same (Figure 7), but this trend is not statistically significant, with p=0.108.

Other studies have also observed an increased number and duration of heatwaves in Brazil, like Mandú et al. (2020) for the amazon region, and extreme events (Borsato and Hiera, 2015). For instance, Bitencourt et al. (2016), who assessed the entire Brazilian territory from the 1960s to 2014, reported a more significant increase in the number and duration of heatwaves starting from 2000. They also observed that the most intense heatwaves occurred after 2000. Similarly, Silveira et al. (2019), who examined four Latin American cities, including three Brazilian ones, from 1970 to 2016, identified a positive trend in the occurrence of heatwaves in all four locations. These positive trends in heatwaves are not restricted to South America cities, as they have been occurring worldwide. Oliveira et al. (2022) used the Excess Heat Factor to analyze heatwave climatology and trends across European urban areas from 1961 to 2018. The results of that study confirm EHF as an effective metric for capturing regional differences, revealing a clear latitudinal gradient and a marked increase in heatwave frequency, duration, and severity in southern Mediterranean Europe, especially over the last three decades. As an outcome of their study, Excess Heat Factor (EHF) was evaluated as a health-relevant heatwave (HW) indicator. Piticar et al. (2017) also applied EHF to study heatwaves from 1961 to 2015 in Romania. The results of that research also pointed out that heat waves are becoming more frequent, longer, and more intense. Wondmagegn et al. (2021) used EHF metric to show how the increase of heatwave intensity increases the cost of the emergency department in South Australia. In China, from the 1990s, abrupt increases in heatwave intensity have also been observed across different regions (Wei et al., 2023).

Furthermore, the risk associated with excessive heat increases throughout the duration of the heatwave, particularly after the fourth day of the event (Kouis et al., 2025).

Figure 8 shows the extreme events, evidencing a nearly 50-year gap between the first two occurrences, October 1972 (a) and October 2020 (b). However, only three years later, two more events occurred, in September and November 2023 (c) and (d), respectively. The 2023 events and the previous occurrences differ significantly in length, with twice as many days of excessive heat; the most recent event lasted at the extreme level for six consecutive days and surpassed prior values by a considerable amount. With such high temperatures, the average severity of the event exceeded the extreme

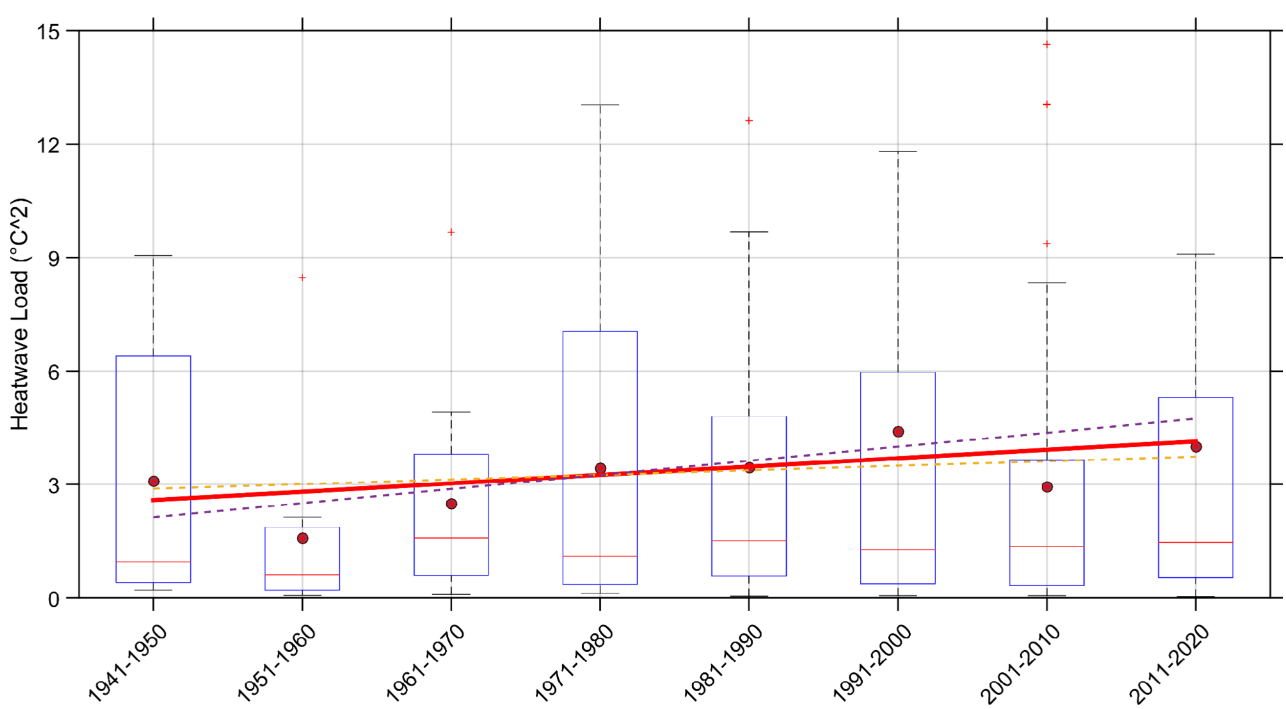

Figure 7 – Decadal trend in heatwave load in the city of São Paulo.

threshold. When we look at the average temperatures for September and November 2023, it is possible to identify how such unique events were possible, as the average temperature deviations were 5 and 2.7°C above the Climatological Normal, respectively (INMET, 2022). With average temperatures rising over the years and positive heat anomalies occurring more intensely, excessive heat days have increased across all seasons, including the unprecedented occurrence in the winter of 2023. Notably, although severe events are more common in the summer, in 2023 they were recorded exclusively in the spring.

The year 2023 was abnormally warm, marked by a strong El-Niño event resulting from the accumulation of heat in the western Pacific following a prolonged La-Niña period (2020–2023). Large-scale climate variability patterns, including teleconnection mechanisms, play a key role in modulating temperature extremes over South America (Souza and Reboita, 2021). Combined with record-high temperatures in the Atlantic and Indian Oceans and other oceanic dynamics (Peng et al., 2025), this contributed to elevated temperatures worldwide, particularly during spring in São Paulo.

Conclusion

The analysis conducted over nearly 90 years using the EHF has demonstrated that over 75% of severe and extreme heat events occur during the summer. São Paulo has been experiencing increasing temperatures in recent years, with longer, more severe, and more frequent heatwaves since the 1970s.

Throughout this study, the most common scenarios for the occurrence of heatwaves in the city were analyzed alongside their seasonality. Particularly severe events were closely examined, as well as the behavior of a "typical" heatwave for proper comparison. The analysis underscores the urgency of addressing the current climate crisis with gravity. It is imperative to implement effective measures to adapt cities to new climate scenarios, aiming to reduce mortality during extreme events, minimizing public costs associated with disasters, which significantly impact both the economy and public health.

The results from nearly nine decades of analysis raise further questions and concerns, as well as suggesting future research to evaluate the EHF index with a more objective classification of severity and to assess the distribution of heat-related mortality rates across different regions and socioeconomic classes within São Paulo. However, the lack

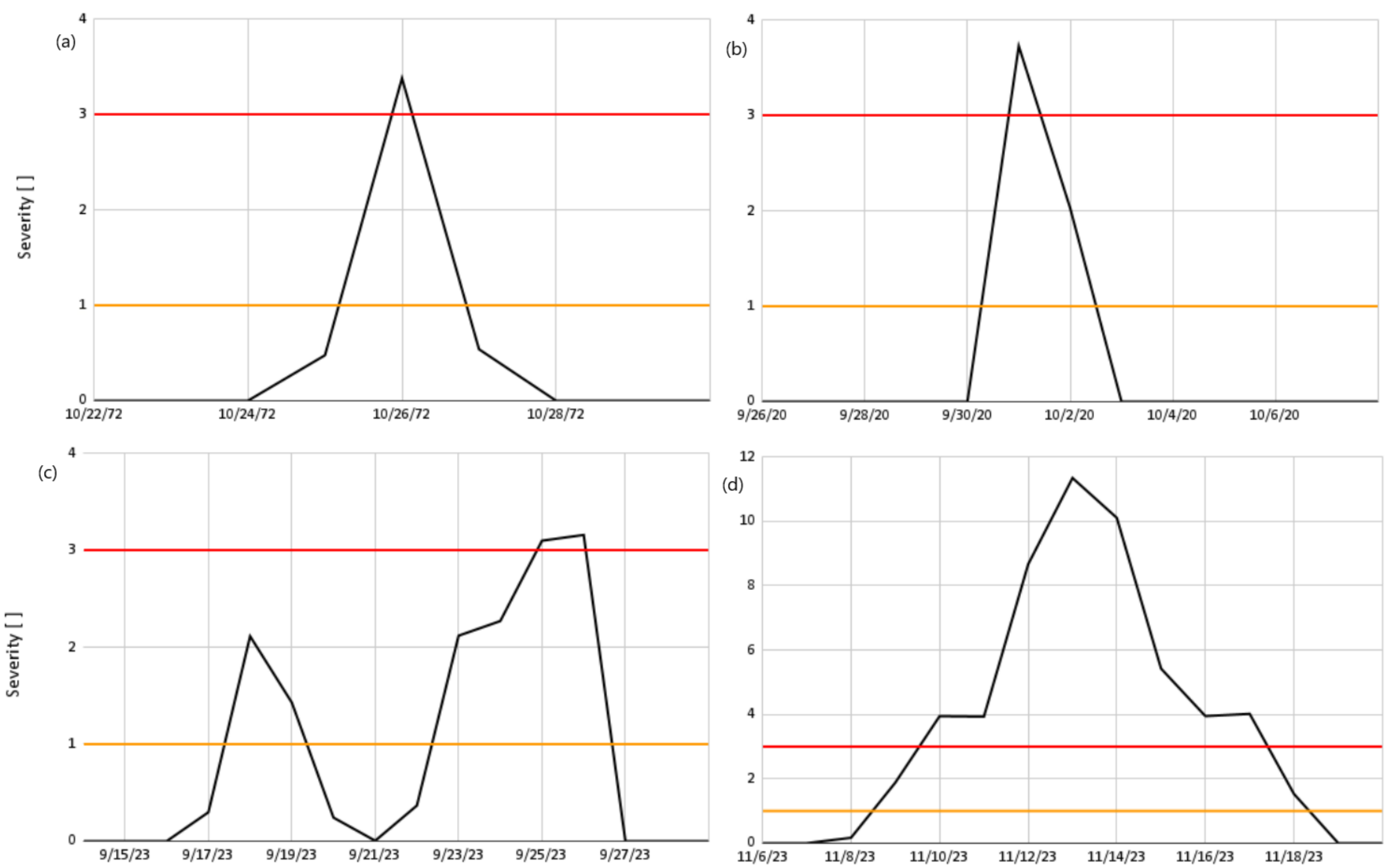

Figure 8 – The historical heat waves events in São Paulo city classified within the EHF category of severe (orange) and extreme (red) according to Nairn et al. (2018) criteria: (a) 24/10/1972, (b) 30/09/2020, (c) 16/09/2023, (d) 07/11/2023.

of meteorological stations spread across São Paulo with decades of data poses a challenge for these studies due to the size of the municipality, as well as reconciling different EHF results with health and socioeconomic data from various regions of São Paulo.

Considering the ongoing trend of severe heatwave events in São Paulo, the findings of this study call for the development of preventive alerts combined with mitigation strategies to safeguard public health (World Health Organization, 2011).

The fact that increasingly severe and persistent heatwaves are observed even at a station site characterized by dense vegetation highlights that green areas are also being significantly affected by extreme heat, implying even more critical conditions in the surrounding urbanized zones. This indicates that the city's thermal conditions have evolved to the point that even greener areas are now exposed to severe heat conditions. It raises an important warning: depending on the scenario, even the city's green areas may no longer be sufficient to mitigate the significant increase in heatwave severity.

Data availability statement

All the datasets used in this study are public and can be requested via the São Paulo University Meteorological Station websites (http://www.estacao.iag.usp.br/sol_dados.php). All analysis codes were specifically developed for this study and are available from the contact author upon request.

Authors' contributions

Matuda, P.H.T.: conceptualization; formal analysis; writing – original draft. **Rosário**, N.M.E.: conceptualization; formal analysis; writing – original draft. **Miragli**, S.G.K.: writing – original draft; writing – review & editing. **Debone**, D.: writing – original draft; writing – review & editing.

References

Bitencourt, D.P.; Fuentes, M.V.; Maia, P.A., 2016. Frequência, duração, abrangência espacial e intensidade das ondas de calor no Brasil. Revista Brasileira de Meteorologia, v. 31, (4), 506-517. https://doi.org/10.1590/0102-778631231420150077.

Borsato, V.A.; Hiera, M.D., 2015. Onda de calor em outubro de 2014 e os sistemas atmosféricos. In: Simpósio Brasileiro de Geografia Física Aplicada, 16., Teresina. Anais… (pp. 222-228) (Accessed May 15, 2026) at:. https://www.researchgate.net/profile/Marcio-Greyck-Correa/publication/309851470_Dinamica_da_precipitacao_pluviometrica_e_vazao_fluvial_para_o_ano_de_1983_na_bacia_hidrografica_do_rio_Piquiri-PR/links/582513fe08ae61258e42ab7d/Dinamica-da-precipitacao-pluviometrica-e-vazao-fluvial-para-o-ano-de-1983-na-bacia-hidrografica-do-rio-Piquiri-PR.pdf#page=75.

Chen, M.; Chen, L.; Zhou, Y.; Hu, M.; Jiang, Y. et al., 2023. Rising vulnerability of compound risk inequality to ageing and extreme heatwave exposure in global cities. npj Urban Sustainability, v. 3, 38. https://doi.org/10.1038/s42949-023-00118-9.

Díaz, J.; Jordán, A.; García, R.; López, C.; Alberdi, J.C. et al., 2001. Heat waves in Madrid 1986–1997: effects on the health of the elderly. International Archives of Occupational and Environmental Health, v. 75, (3), 163-170. https://doi.org/10.1007/s00420-001-0290-4.

Diniz, F.R.; Gonçalves, F.L.T.; Sheridan, S., 2020. Heat wave and elderly mortality: historical analysis and future projection for Metropolitan Region of São Paulo, Brazil. Atmosphere, v. 11, (9), 933. https://doi.org/10.3390/atmos11090933.

Fernandez-Medina, R.D.; Peixoto, E.M.; Rodrigues, D.; Said, R.; Holanda, C.A. et al., 2025. Excess mortality associated with extreme heat in Rio de Janeiro, Brazil, 2023. Pan American Journal of Public Health, v. 49, e76. https://doi.org/10.26633/RPSP.2025.76.

Fouillet, A.; Rey, G.; Wagner, V.; Laaidi, K.; Empereur-Bissonnet, P.; Le Tertre, A. et al., 2008. Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. International Journal of Epidemiology, v. 37, (2), 309-317. https://doi.org/10.1093/ije/dym253.

Fundação Sistema Estadual de Análise de Dados (SEADE), 2022. Cidade para os idosos. SEADE, São Paulo (Accessed November 29, 2023) at:. https://www.seade.gov.br/cidade-para-os-idosos/.

Gao, S.; Chen, Y.; Chen, D.; He, B.; Gong, A. et al., 2024. Urbanization-induced warming amplifies population exposure to compound heatwaves but narrows exposure inequality between global North and South cities. npj Climate Atmospheric Sciences, v. 7, 154. https://doi.org/10.1038/s41612-024-00708-z.

Gao, S.; Chen, Y.; Chen, D.; He, B.; Li, K. et al., 2026. More intense and equal compound heatwaves driven by urbanization. npj Urban Sustainability, v. 6, 54. https://doi.org/10.1038/s42949-026-00363-8.

Gouveia, N.; Hajat, S.; Armstrong, B., 2003. Socioeconomic differentials in the temperature–mortality relationship in São Paulo, Brazil. International Journal of Epidemiology, v. 32, (3), 390-397. https://doi.org/10.1093/ije/dyg077.

Guo, Y.; Gasparini, A.; Li, S.; Sera, F.; Vicedo-Cabrera, A.M. et al., 2018. Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. Public Library of Science Medicine, v. 15, (7), E1002629. https://doi.org/10.1371/journal.pmed.1002629.

Hundessa, S.; Huang, W.; Xu, R.; Yang, Z.; Zhao, Q. et al., 2025. Global excess deaths associated with heatwaves in 2023 and the contribution of human-induced climate change. The Innovation, v. 6, (10), 101110. https://doi.org/10.1016/j.xinn.2025.101110.

Instituto Brasileiro de Geografia e Estatística (IBGE), 2019. Cidades e Estados: São Paulo. IBGE, Rio de Janeiro (Accessed November 22, 2024) at:. https://cidades.ibge.gov.br/brasil/sp/sao-paulo/panorama.

Instituto Brasileiro de Geografia e Estatística (IBGE), 2022. Censo Brasileiro de 2022. IBGE, Rio de Janeiro (Accessed May 15, 2026) at:. https://www.ibge.gov.br/estatisticas/sociais/saude/22827-censo-demografico-2022.html.

Instituto Nacional de Meteorologia (INMET), 2022. Normais Climatológicas do Brasil: 1991-2020. INMET, Brasília, DF (Accessed May 15, 2026) at:. https://portal.inmet.gov.br/uploads/normais/NORMAISCLIMATOLOGICAS.pdf.

Intergovernmental Panel on Climate Change (IPCC), 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva. https://doi.org/10.59327/IPCC/AR6-9789291691647.

Jangi, M.R.; Zarrin, A.; Mofidi, A.; Dadashi-Roudbari, A., 2024. Intensifying heatwave trends in Iran based on observational data using excess heat factor (EHF). Natural Hazards, v. 120, 2073-2090. https://doi.org/10.1007/s11069-023-06281-7.

Kouis, P.; Psistaki, K.; Yiallouros, P.K.; Paschalidou, A.K., 2025. The role of heatwave characteristics in cardiovascular mortality in the Eastern Mediterranean region. Environment International, v. 201, 109563. https://doi.org/10.1016/j.envint.2025.109563.

Lamb, W.F.; Wiedmann, T.; Pongratz, J.; Andrew, R.; Crippa, M. et al., 2021. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environmental Research Letters, v. 16, (7), 049502. https://doi.org/10.1088/1748-9326/abee4e.

Liu, X.; He, B.; Guo, L.; Huang, L.; Chen, D., 2020. Similarities and differences in the mechanisms causing the European summer heatwaves in 2003, 2010, and 2018. Earth's Future, v. 8, (4), e2019EF001386. https://doi.org/10.1029/2019EF001386.

Loridan, T.; Coates, L.; Frontiers, R.; Argüeso, D.; Perkins-Kirkpatrick, S.E., 2016. The excess heat factor as a metric for heat-related fatalities: Defining heatwave risk categories. Australian Journal of Emergency Management, v. 31, (4), 31-37 (Accessed May 15, 2026) at:. https://knowledge.aidr.org.au/resources/ajem-oct-2016-the-excess-heat-factor-as-a-metric-for-heat-related-fatalities-defining-heatwave-risk-categories.

Mandú, T.B.; Gomes, A.C.S.; Costa, G.B.; Neves, T.T.A., 2020. Avaliação de tendência nas ondas de calor registradas em Manaus/AM, Brasil. Revista Brasileira de Climatologia, v. 27, 405-425. https://doi.org/10.5380/abclima.v27i0.73931.

Matthews, T.; Raymond, C.; Foster, J.; Baldwin, J.W.; Ivanovich, C. et al., 2025. Mortality impacts of the most extreme heat events. Nature Reviews Earth & Environment, v. 6, 193-210. https://doi.org/10.1038/s43017-024-00635-w.

McGeehin, M.A.; Mirabelli, M., 2001. The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. Environmental Health Perspectives, v. 109, (Suppl. 2), 185-189. https://doi.org/10.1289/ehp.109-1240665.

Meehl, G.A.; Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science, v. 305, (5686), 994-997. https://doi.org/10.1126/science.1098704.

Nairn, J.; Bi, P.; Ostendorf, B., 2018. Performance of excess heat factor severity as a global heatwave health impact index. International Journal of Environmental Research and Public Health, v. 15, (11), 2494. https://doi.org/10.3390/ijerph15112494.

Nairn, J.R.; Fawcett, R., 2013. Defining heatwaves: heatwave defined as a heat-impact event servicing all community and business sectors in Australia. Centre for Australian Weather and Climate Research, Melbourne.

Nairn, J.R.; Fawcett, R., 2014. The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity. International Journal of Environmental Research and Public Health, v. 12, (1), 227-253. https://doi.org/10.3390/ijerph120100227.

Nicholls, N.; Skinner, C.; Loughnan, M.; Tapper, N., 2008. A simple heat alert system for Melbourne, Australia. International Journal of Biometeorology, v. 52, 375-384. https://doi.org/10.1007/s00484-007-0132-5.

Odunmorayo, M.T.; Alani, B.O.; Adefisan, E.A., 2025. Projected change in occurrence and severity of heatwaves over West Africa as simulated by CMIP6 models. Journal of Disaster Science and Management, v. 1, 16. https://doi.org/10.1007/s44367-025-00017-z.

Oliveira, A.; Lopes, A.; Soares, A., 2022. Excess heat factor climatology, trends, and exposure across european functional urban areas. Weather and Climate Extremes, v. 36, 100455. https://doi.org/10.1016/j.wace.2022.100455.

Pattenden, S.; Nikiforov, B.; Armstrong, B.G., 2003. Mortality and temperature in Sofia and London. International Journal of Epidemiology. Community Health, v. 57, (8), 628-633. https://doi.org/10.1136/jech.57.8.628.

Peng, Q.; Xie, S.P.; Miyamoto, A.; Deser, C.; Zhang, P. et al., 2025. Strong 2023–2024 El Niño generated by ocean dynamics. Nature Geoscience, v. 18, 471-478. https://doi.org/10.1038/s41561-025-01700-9.

Perkins-Kirkpatrick, S.; Lewis, S., 2022. Increasing trends in regional heatwaves. Nature Reviews Earth & Environment, v. 11, 3357. https://doi.org/10.1038/s41467-020-16970-7.

Piticar, A.; Croitoru, A.-E.; Ciupertea, F.-A.; Harpa, G.-V., 2017. Recent changes in heat waves and cold waves detected based on excess heat factor and excess cold factor in Romania. International Journal of Climatology, v. 38, (4), 1777-1793. https://doi.org/10.1002/joc.5295.

Reis, N.C.S.; Boiaski, N.T.; Ferraz, S.E.T., 2019. Characterization and spatial coverage of heat waves in subtropical Brazil. Atmosphere, v. 10, (5), 284. https://doi.org/10.3390/atmos10050284.

Robine, J.M.; Cheung, S.L.K.; Le Roy, S.; Oyen, H.V.; Griffiths, C. et al., 2008. Death toll exceeded 70,000 in Europe during the summer of 2003. Comptes Rendus Biologies, v. 331, (2), 171-178. https://doi.org/10.1016/j.crvi.2007.12.001.

Rohini, P.; Rajeevan, M.; Srivastava, A.K., 2016. On the variability and increasing trends of heat waves over India. Scientific Reports, v. 6, 26153. https://doi.org/10.1038/srep26153.

Santos, P.C.; Drumond Jr, M.; Uehara, M.K.; Hangai, M.F.; Israel, V. et al., 2014. A onda de calor de fevereiro de 2014 e o excesso de mortes no município de São Paulo. Boletim Análise, v. 9 (Accessed September 18, 2022) at:. https://pesquisa.bvsalud.org/portal/resource/pt/biblio-940653.

Saxena, S.; Agrawal, S.; Basu, D., 2024. EHF based Heatwave Identification and its Impact on Urban Heat Island Intensity. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, v. X-3-2024, 377–382. https://doi.org/10.5194/isprs-annals-X-3-2024-377-2024.

Silva, L.P.; Santos, P.R.A.; Ribeiro, G.M.S.; Medeiros, S.E.L.; Silva, W.K.M. et al., 2022. Métodos estatísticos para detectar tendências em dados climáticos históricos: revisão bibliográfica. Cadernos de Ciência & Tecnologia, v. 39, (1), 26929. https://doi.org/10.35977/0104-1096.cct2022.v39.26929.

Silveira, R.B.; Alves, M.P.A.; Bitencourt, D.P., 2019. Ondas de calor nas capitais do Sul do Brasil e Montevidéu - Uruguai. Revista Brasileira de Geografia Física, v. 12, (4), 1259-1276. https://doi.org/10.26848/rbgf.v12.4.p1259-1276.

Soomro, S.-E.-H.; Boota, M.W.; Soomro, G.-E.-Z.; Soomro, M.H.A.A.; Hu, C. et al., 2025. Urban cities heatwaves vulnerability and societal responses towards hazard zoning: Social media real-time based heatwave detection using deep learning. Sustainable Cities and Society, v. 125, 106360. https://doi.org/10.1016/j.scs.2025.106360.

Souza, C.A.; Reboita, M.S., 2021. Ferramenta para o Monitoramento dos Padrões de Teleconexão na América do Sul. Terrae Didatica, v. 17, e02109. https://doi.org/10.20396/td.v17i00.8663474.

Tolika, K., 2019. Assessing heat waves over Greece using the excess heat factor (EHF). Climate, v. 7, (1), 9. https://doi.org/10.3390/cli7010009.

United Nations Human Settlements Programme (2022). World Cities Report 2022: Envisaging the Future of Cities (Accessed October 9, 2022) at:. https://unhabitat.org/sites/default/files/2022/06/wcr_2022.pdf.

Varghese, B.M.; Hansen, A.; Nitschke, M.; Nairn, J.; Hanson-Easey, S. et al., 2019. Heatwave and work-related injuries and illnesses in Adelaide, Australia: a case-crossover analysis using the Excess Heat Factor (EHF) as a universal heatwave index. International Archives of Occupational and Environmental Health, v. 92, 263-272. https://doi.org/10.1007/s00420-018-1376-6.

Vicedo-Cabrera, A.M.; Scovronick, N.; Sera, F.; Royé, D.; Schneider, R. et al., 2021. The burden of heat-related mortality attributable to recent human-induced climate change. Nature Climate Change, v. 11, 492-500. https://doi.org/10.1038/s41558-021-01058-x.

Wei, J.; Han, W.; Wang, W.; Zhang, L.; Rajagopalan, B., 2023. Intensification of heatwaves in China in recent decades: Roles of climate modes. npj Climate Atmospheric Science, v. 6, 98. https://doi.org/10.1038/s41612-023-00428-w.

Wen, B.; Wu, Y.; Guo, Y.; Gasparrini, A.; Tong, S. et al., 2024. Comparison for the effects of different components of temperature variability on mortality: A multi-country time-series study. Environment International, v. 187, 108712. https://doi.org/10.1016/j.envint.2024.108712.

Wilks, D.S., 1995. Statistical methods in the atmospheric sciences, second edition. International Geophysics Series, Vol. 59, London, Academic Press, 464 pp.

Wondmagegn, B.Y.; Xiang, J.; Dear, K.; Williams, S.; Hansen, A. et al., 2021. Impact of heatwave intensity using excess heat factor on emergency department presentations and related healthcare costs in Adelaide, South Australia. Science of the Total Environment, v. 781, 146815. https://doi.org/10.1016/j.scitotenv.2021.146815.

World Health Organization, 2011. Public health advice on preventing health effects of heat. World Health Organization (Accessed December 3, 2022) at:. https://www.who.int/publications/i/item/WHO-EURO-2011-2510-42266-58691.

World Health Organization, 2015. World report on ageing and health. World Health Organization (Accessed October 9, 2022) at:. https://apps.who.int/iris/bitstream/handle/10665/186463/9789240694811_eng.pdf?sequence=1&isAllowed=y.

You, Q.; Jiang, Z.; Kong, L.; Wu, Z.; Bao, Y. et al., 2017. A comparison of heat wave climatologies and trends in China based on multiple definitions. Climate Dynamics, v. 48, (11-12), 3975-3989. https://doi.org/10.1007/s00382-016-3315-0.

Zhou, Q.-Y.; Gao, M.-N.; Yang, J.; Sun, X.-Y.; Lu, Y.-Y. et al., 2025. Future changes in population exposure to intensified heatwaves over three major urban agglomerations in China based on excess heat factor. Advances in Climate Change Research, v. 16, (1), 12-24. https://doi.org/10.1016/j.accre.2024.12.009.

Zhou, Y.; Gu, S.; Yang, H.; Ge, Z.; Dong, G; Zhao, Y.; Yang, Q. Escalating heatwave exposure of the elderly across China. Environmental Research, v. 282, 2025. https://doi.org/10.1016/j.envres.2025.121986.