






Case Study of an Extreme Heat Wave in Rio de Janeiro on November 2023: Synoptic Conditions and Climatological Trends

Estudo de Caso de uma Onda de Calor Extrema no Rio de Janeiro em Novembro de 2023: Condições Sinóticas e Tendências Climatológicas

Claudine Dereczynski¹ , Wanderson Luiz-Silva¹ , Anna Carolina Bazzanela² ,
Airon Bodstein³  & Sin Chan Chou⁴ 

¹Universidade Federal do Rio de Janeiro, Instituto de Geociências, Departamento de Meteorologia, Rio de Janeiro, RJ, Brasil

²Universidade Federal do Rio de Janeiro, Instituto de Geociências, Departamento de Meteorologia, Programa de Pós-Graduação em Meteorologia, Rio de Janeiro, RJ, Brasil

³Universidade Federal Fluminense, Mestrado em Defesa e Segurança Civil, Niterói, RJ, Brasil

⁴Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, SP, Brasil

E-mails: claudine.dereczynski@igeo.ufrj.br; wanderson@igeo.ufrj.br; bazzanelaannacarolina@gmail.com; abodstein@id.uff.br; chou.chan@inpe.br

Abstract

This article is a case study to analyze the synoptic and climatological aspects of an heat wave in Rio de Janeiro, located in the Southeast Region of Brazil, during November 2023. This work aims to investigate whether the high temperatures recorded on November 17 and 18, 2023, during a concert of an American singer, could be considered an extreme weather event. On the first day of the concert, the 17th, many people fell ill due to the extreme heat, and a 23-year-old female died, a victim of cardiorespiratory arrest caused by thermal exhaustion. On November 18, 11 meteorological stations recorded a maximum temperature (TX) equal to or over 40 °C, and the highest TX in the city was 43.5 °C. At a station located in the coldest area of the city, the highest TX (39.6°C) in its entire historical record (1967-2023) was also recorded on the 18th. Such extremely high temperatures occurred during a prefrontal situation and at the end of a heat wave that lasted eight days. Analysis of the diurnal cycle of the air temperature on the 17th and 18th indicated that the minimum temperature (TN) was about 5 to 6 °C above its climatology; the TX was approximately 13 °C above its climatological value, and high temperatures lasted all afternoon. On the 18th, the Heat Index reached 55.1 °C at 14:00 and 15:00 LT, characterizing a state of medical emergency during seven hours. In terms of climate, in addition to the increase in intensity and frequency of warm extremes over the city, the El Niño phenomenon (EN) was configured in the Pacific Ocean from April 2023 to May 2024, causing a drier and warmer spring in Southeast Brazil. This concert represented a milestone for the city regarding the need for local public policies to regulate massive crowd-gathering events during heat wave episodes. Finally, it is possible to state that the event was extreme, caused by the combination of a heat wave, in a prefrontal situation, during an EN event, and in a context of climate change.

Keywords: Heat wave; Global warming; El Niño

Resumo

Este artigo é um estudo de caso que analisa os aspectos sinóticos e climatológicos de uma onda de calor no Rio de Janeiro, localizado na Região Sudeste do Brasil, durante o mês de novembro de 2023. O objetivo deste trabalho é investigar se as elevadas temperaturas registradas nos dias 17 e 18 de novembro, durante um show de uma cantora norte americana, poderiam ser consideradas como um evento extremo. No primeiro dia do show, dia 17, muitas pessoas passaram mal devido ao calor extremo, e uma jovem de 23 anos faleceu, vítima de parada cardiorespiratória causada por exaustão térmica. No dia 18 de novembro, 11 estações meteorológicas registraram temperatura máxima (TX) igual ou superior a 40 °C, e a maior TX na cidade foi de 43,5 °C. Na estação localizada na área mais fria da cidade, a maior TX (39,6°C) de toda sua série histórica (1967-2023) foi também registrada no dia 18. Tais temperaturas extremamente elevadas ocorreram durante uma situação pré-frontal e no final de uma onda de calor que durou oito dias. Análise dos ciclos diurnos dos dias 17 e 18 indicaram que a temperatura mínima (TN) esteve aproximadamente 5 a 6 °C acima de seu valor climatológico; TX esteve cerca de 13 °C mais elevada do que a climatologia e temperaturas muito altas foram registradas por toda a tarde. No dia 18, o Índice de Calor atingiu 55,1 °C às 14h e 15h, caracterizando-se um estado de emergência médica por um período de sete horas. Em termos de clima, além do aumento na intensidade e frequência de extremos quentes sobre a cidade, o fenômeno El Niño (EN) esteve configurado sobre o Oceano Pacífico, de abril de 2023 a maio de 2024, causando uma primavera mais quente e mais seca no Sudeste do Brasil. O show representou um marco na cidade em relação a necessidade de políticas públicas para regulamentar eventos com grande concentração de público durante episódios de ondas de calor. Finalmente, é possível afirmar que o evento foi extremo, causado por uma combinação de onda de calor, em situação pré-frontal durante um evento de EN, e no contexto de aquecimento global.

Palavras-chave: Onda de calor; Aquecimento global; El Niño

1 Introduction

On November 8, 2023, the Brazilian National Institute of Meteorology (INMET) warned about the eighth heat wave to occur in Brazil in the year, and to be expected for the Midwest and Southeast Brazil's regions, including the entire State of Rio de Janeiro (INMET 2023), as a "major hazard." In these areas, temperatures of 5 °C above average were predicted for more than five consecutive days, thus characterizing a heat wave, according to the definition adopted by INMET (INMET 2023). Temperatures remained high for several days that week, reaching a maximum above 40 °C in several weather stations on November 18, when the concert of an American pop singer (Taylor Swift) caused a major crowd gathering in the city of Rio de Janeiro. It is important to note that these high temperatures occurred even before the beginning of summer 2024 (December/2023, January and February/2024).

On the first day of the concert, November 17, 2023, many people fell ill due to the extreme heat at the Nilton Santos Olympic Stadium, and a 23-year-old female died due to cardiorespiratory arrest caused by thermal exhaustion (AP News 2023). On that day, despite the intense heat, the entry of several items inside the stadium was prohibited, including bottles of water and food.

The singer's second concert in Rio de Janeiro, scheduled for November 18, was postponed to November 20 due to the extreme temperatures recorded that day. In this situation, after the death of the student on November 17, under high temperatures throughout the city and the forecast of extreme temperatures predicted at least five days in advance, logically, the event on November 18 should have been postponed in the morning. However, the communication of the postponement of the show only occurred at 17:30 Local Time (LT) on the same day, that is, one hour before the start of the opening show presentation. Thus, once again, thousands of fans lined up for hours outside the Nilton Santos Olympic Stadium, and several people fell ill due to the intense heat.

According to the National Oceanic and Atmospheric Administration (NOAA), November 2023 was the warmest November globally and in South America, considering a 174-year historical record (NOAA 2023a). The global average temperature in November 2023 was 1.44 °C above the 20th-century average of 12.9 °C. In addition, the entire year of 2023 was also considered the hottest year in the historical series (NOAA 2023b). Marengo and Nobre (2024) affirm that Brazil had its warmest year in 2023, with 9 heat waves. In the last decade, there has been an almost sevenfold increase in the incidence of heat waves in Brazil (Marengo & Nobre 2024).

Regarding natural climate variability, the El Niño phenomenon causes more frequent heat waves in Brazil, as occurred in 2023 (National Geographic 2023). According to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC 2021; Seneviratne et al. 2021), it is virtually certain that the duration, frequency, and intensity of extreme hot events such as heat waves are increasing due to human activity. The same report states that an increase in the intensity and frequency of warm extremes is very likely to occur, even considering an average global warming of only 1.5 °C (IPCC 2021).

Like the rest of the world, South America has experienced heat waves more frequently and prolonged in recent years. According to Dereczynski et al. (2013), in Rio de Janeiro, the length of heat waves is increasing with a statistical significance of 1.7 days/decade. The authors also show that warm (cold) days and nights are more (less) frequent, consistent with a global warming scenario.

Monteiro dos Santos et al. (2024) found an increase in the frequency and duration of heat waves in some Brazilian Metropolitan regions, including Rio de Janeiro from 1970 to 2020. In Rio de Janeiro, throughout the 1970s and '80s, the heat wave frequency (duration) was 2.5 events/year (4.0 days), while in the 2000s and '10s, the frequency (duration) increased to 4.0 events/year (5.0 days). Considering the Brazilian urban areas, over the 2000–2018 period, 48,075 excessive deaths were attributed to the growing number of heat waves (>20 times the number of landslide-related deaths for the same period). Nevertheless, the authors affirm that extreme heat events are a neglected disaster in Brazil.

Rivera et al. (2023) analyzed two heat waves that occurred in late November (23 to 29) and early December (4 to 12) 2022, affecting north-central Argentina, southern Bolivia, central Chile, and most of Paraguay and Uruguay. The return period of the December 2022 heat wave, calculated for the present climate, was 20 years, meaning that events like that have approximately a 5% chance of occurring each year today. In these two events, several stations recorded maximum temperatures above 40 °C. The attribution study developed by Rivera et al. (2023) showed that anthropogenic climate change made the December 2022 event sixty times more likely. A heatwave with a 20-year return period could have been 1.4 °C less warm in a world without global warming.

This article aims to answer the question: Can the high temperatures recorded in Rio de Janeiro on November 17 and 18, 2023, be considered an extreme weather event? This work is divided into four sections, including this Introduction. Section 2 describes the methodology and data used in this work. Section 3 presents the results, with the climatology and trends of air temperature extremes over

the city, and the heat wave case study. The conclusions are summarized in Section 4.

2 Data and Methodology

2.1 Meteorological Surface Stations

Time series of meteorological variables from 16 surface meteorological stations located in the city of Rio de Janeiro were used. The map with the location of these stations and the Nilton Santos Olympic Stadium is shown in Figure 1. The Nilton Santos Olympic Stadium is located in the North Zone, one of the hottest regions of the city (Dereczynski et al. 2011). Unfortunately, the weather station closest to the Nilton Santos Olympic Stadium (Irajá station of Alerta Rio) was under maintenance during the week of the concert, and, therefore, it was not possible to use its data series.

The 16 meteorological stations used in this work are listed in Table 1 in the following order: i) Alto da Boa Vista conventional station (ABVI – (1)), located at an altitude of 347 m in a vegetated area close to the Tijuca Forest (the world’s largest urban forest), containing the longest data series (1967-2023) of Rio de Janeiro; ii) 5 meteorological stations located at Rio de Janeiro’s airports, three belonging

to the Department of Airspace Control (DECEA) and two belonging to NAV Brasil Air Navigation Services; iii) 6 automatic stations of “Alerta Rio”; and iv) 4 INMET’s automatic stations.

The data series obtained from the 16 meteorological stations are air temperature (T in °C), maximum temperature (TX in °C), minimum temperature (TN in °C), atmospheric mean sea level pressure (MSLP in hPa), Precipitation (Pr in mm), relative humidity (RH in %), wind velocity (Vel in m/s), wind direction (Dir in degrees) and significant weather.

The meteorological station with the longest data series (1967-2023), ABVI (1), is used to calculate climatic extremes indices. November’s climatology is calculated using Rio de Janeiro Airports data series (SBAF (2), SBGL (3), SBSC (4), SBRJ (5)) and SCRIS (12). The other stations are used to present the data recorded during the week of the concert (November 13-20, 2023).

2.2 Satellite Images

Images from the GOES 16 satellite, on channel 14, every 15 minutes for the period November 13-20, 2023, were obtained from the website of the National Institute for Space Research (INPE; <https://satellite.cptec.inpe.br/acervo/goes16.formulario.logic>).

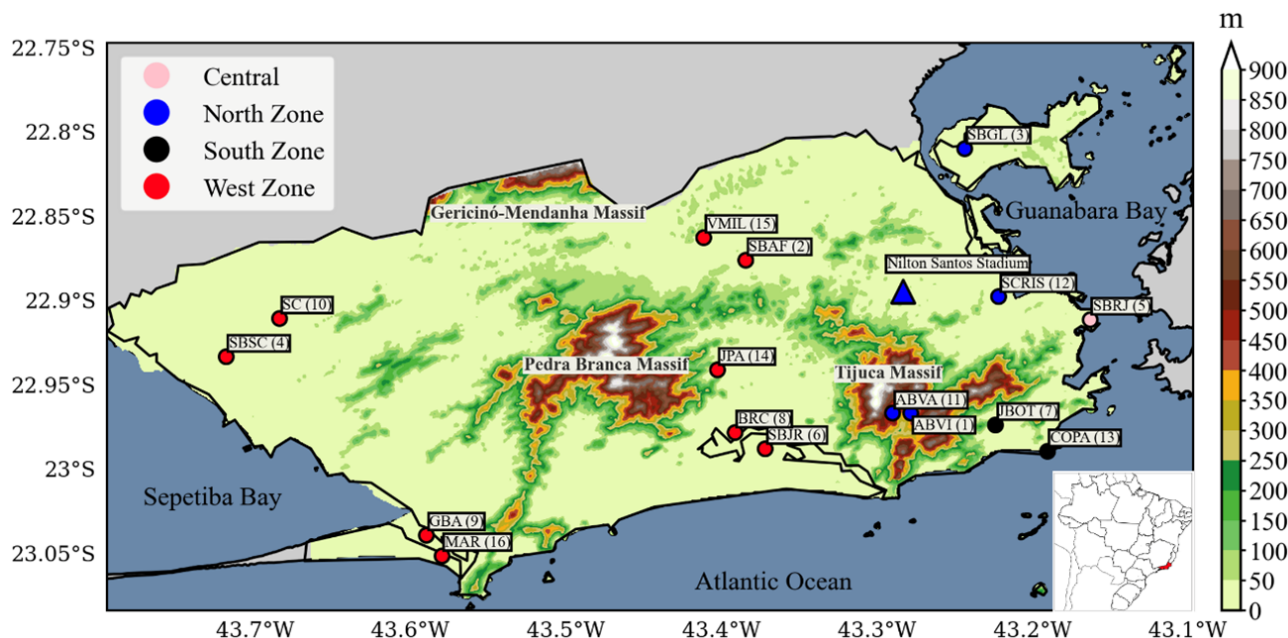


Figure 1 Topography (m) of Rio de Janeiro city and location of the 16 meteorological stations used in this work. The location of the Nilton Santos Olympic Stadium is highlighted with a blue triangle.



Table 1 Information from the INMET, DECEA, NAV Brasil and Alerta Rio meteorological stations used in this work.

Station Acronym (Number)	Station Name (Institution)	Latitude (°S)	Longitude (°W)	Altitude (m)	Period (Percentage of failures)	Data (Frequency)
INMET, DECEA and NAV Brasil Conventional Stations						
ABVI (1)	Alto da Boa Vista – 83007 (INMET)	22.9658	43.27927	347.1	Nov. 1967-2023 (5.2%)	TX, TN e Pr (daily)
SBAF (2)	Afonso Airport – SBAF (DECEA)	22.8750	43.3844	6.0	Nov. 2001-2023 (0.4%)	T, RH, MSLP, Vel, Dir, significant weather (hourly, from 07:00 to 21:00 LT)
SBGL (3)	Rio de Janeiro International Airport – SBGL (DECEA)	22.8088	43.2436	8.0	Nov. 2001-2023 (0.1%)	T, RH, MSLP, Vel, Dir, significant weather (hourly)
SBSC (4)	Santa Cruz Airport – SBSC – (DECEA)	22.9322	43.7189	3.0	Nov. 2001-2023 (0.1%)	T, RH, MSLP, Vel, Dir, significant weather (hourly)
SBRJ (5)	Santos Dumont Airport – SBRJ – (NAV Brasil)	22.9103	43.1631	3.0	Nov. 2001-2023 (0.1%)	T, RH, MSLP, Vel, Dir, significant weather (hourly)
SBJR (6)	Jacarepaguá Airport – SBJR (NAV Brasil)	22.9867	43.3719	5.0	Nov. 2001-2023 (0.1%)	T, RH, MSLP, Vel, Dir, presente weather (hourly, from 7:00 to 21:00 LT)
Alerta Rio and INMET Automatic Stations						
JBOT (7)	Jardim Botânico (Alerta Rio)	22.9728	43.2239	0.0	Nov. 13-20, 2023 (0%)	T, RH, Pr (15 min)
BRC (8)	Barra/Rio Centro (Alerta Rio)	22.9772	43.3916	0.0	Nov. 13-20, 2023 (0%)	T, RH, Pr (15 min)
GBA (9)	Guaratiba (Alerta Rio)	23.0503	43.5947	0.0	Nov. 13-20, 2023 (0%)	Pr (15 min)
SC (10)	Santa Cruz (Alerta Rio)	22.9094	43.6844	15.0	Nov. 13-20, 2023 (0%)	T, RH, Pr (15 min)
ABVA (11)	Alto da Boa Vista (Alerta Rio)	22.9658	43.2783	355.0	Nov. 13-20, 2023 (0%)	T, RH, Pr (15 min)
SCRIS (12)	São Cristóvão (Alerta Rio)	22.8967	43.2217	25.0	2001-2023 Nov. (4.4%)	T, RH, MSLP, Pr, Vel, Dir (15 min)
COPA (13)	Forte de Copacabana – A652 (INMET)	22.9883	43.1906	25.6	Nov. 13-20, 2023 (0%)	T, RH, MSLP, Pr, Vel, Dir (hourly)
JPA (14)	Jacarepaguá – A636 (INMET)	22.9400	43.4028	20.0	Nov. 13-20, 2023 (0%)	T, RH, MSLP, Pr, Vel, Dir (hourly)
VMIL (15)	Vila Militar – A621 (INMET)	22.8614	43.4112	30.4	Nov. 13-20, 2023 (0%)	T, RH, MSLP, Pr, Vel, Dir (hourly)
MAR (16)	Marambaia – A602 (INMET)	23.0503	43.5956	12.0	Nov. 13-20, 2023 (0%)	T, RH, MSLP, Pr, Vel, Dir (hourly)

2.3 ERA5 Data

Atmospheric mean sea level pressure fields (in hPa) were obtained from the European Centre for Medium-Range Weather Forecast (ECMWF) Reanalysis v5 (ERA5; <https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>), with a 31 km horizontal resolution (Hersbach et al. 2020).

2.4 Climate Extremes Indices

There is a consensus in the scientific community that any modification in the frequency and/or intensity of

extreme weather events generates profound impacts on nature and society. So, the Joint World Meteorological Organization (WMO) Commission for Climatology (CCI)/World Climate Research Program (WCRP) Expert Team on Climate Change Detection and Indices (ETCCDI; <https://www.wcrp-climate.org/data-etccdi>) created a set of climate extremes indices based on daily TX, TN and Pr data that provide a comprehensive overview of temperature and precipitation statistics focusing mainly on extreme aspects (Karl et al. 1999; Frich et al. 2002). The temperature extremes used in this work are listed in Table 2.

Table 2 Temperature extreme indices analyzed in this work.

ID	Index name	Definition and Unit
TXmean	Mean TX	Mean value of TX [°C]
TNmean	Mean TN	Mean value of TN [°C]
TX90p	Warm days	Number of days when TX > 90th percentile [days]
TN90p	Warm nights	Number of nights when TN > 90th percentile [days]
TXx	Max TX	Maximum value of TX [°C]
TNx	Max TN	Maximum value of TN [°C]
TR20	Tropical nights	Number of days when TN > 20 °C [days]
SU30	Summer days	Number of days when TX > 30 °C [days]
WSDI	Warm Spell Duration Index	Count of days with at least 6 consecutive days when TX > 90th percentile [days]

2.5 Thermal Discomfort

According to Fanger (1970), thermal discomfort is the condition that expresses the individual's dissatisfaction with the thermal environment. When there is an imbalance between the heat produced by the body and the heat lost by it, there is a feeling of thermal discomfort. If the heat lost is greater than that generated, a person will feel cold; if it is lower, the sensation will be hot.

There are several thermal discomfort indexes; one is the Heat Index (HI), which is used for hot periods and considers the effect of humidity on temperature. The higher the humidity and air temperature, the greater the discomfort and the higher the HI. This is because when the air is saturated with water vapor, it is more difficult to evaporate the body's sweat, which is the process responsible for "cooling" our body.

The values of HI (°C) presented in the Supplementary Material (Figure SM1) are calculated according to the methodology proposed by NOAA (<https://www.wpc.ncep.noaa.gov/html/heatindex.shtml>). Thom's Discomfort Index (TDI; Thom 1959) ranging from class 1 to class 6, is also showed in Figure SM1.

3 Results

3.1 Climatology of Rio de Janeiro City

Rio de Janeiro (Figure 1) has a predominantly hot and humid climate in the summer and cold and dry cold and dry climate winter (Alvares et al. 2014). The city is influenced by the presence of the Atlantic Ocean to the south, Guanabara Bay to the east, and Sepetiba Bay to the west. Three massifs mark the topography of Rio de Janeiro: Gericinó-Mendanha to the north, the Tijuca massif to the south, and the Pedra Branca massif to the west (Solórzano et al. 2016). All other city areas are lowlands with an average

elevation of 20 meters. These altimetric differences in line with the seasonal cycle of solar radiation confer a marked variability in the air temperature in the city (Dereczynski et al. 2013).

Figure 2 shows the annual cycle of TXmean and TNmean at the Alto da Boa Vista (INMET), the coldest station in Rio de Janeiro, from 1991 to 2020. A typical tropical climate is predominant, with hot summers and cold winters. The warmest quarter is from January to March (JFM) when the median TXmean (TNmean) is between 29.1 °C and 30.7 °C (20.3 °C and 21.1 °C). During the warmest season, the longer insolation contributes to the highest temperatures during the day, while the shortest nights do not allow much heat to be lost (Peixoto & Oort 1992). The coldest quarter extends from June to August (JJA), with median TXmean (TNmean) oscillating between 24.1 °C and 24.7 °C (15.1 °C and 15.6 °C). The shorter insolation and the incursion of cold masses from the polar region contribute to lower temperatures in these months (Luiz-Silva & Dereczynski 2014).

In November, the median TXmean (TNmean) is 26.6 °C (18.5 °C), and TX achieves 39.6 °C, without outliers. It is also observed that the variability of TX is greater than that of TN. Considering the 30 years (1991-2020) analyzed, the difference from TX maximum to TX minimum was around 20 °C monthly, while the difference from TN maximum to TN minimum was around 15 °C. This may be associated with the cloudiness amount effect, which exerts a more significant impact on TX compared to TN. In general, TX occurs during the afternoon; on a cloudy (clear) day, TX will drop (increase) strongly. On the other hand, as TN generally occurs before dawn, on a cloudy (clear) day, TN will (drop) not drop so much.

Rio de Janeiro is strongly influenced on the synoptic scale by the South Atlantic Subtropical High (SASH) for much of the year (Cavalcanti et al. 2009). In the city near

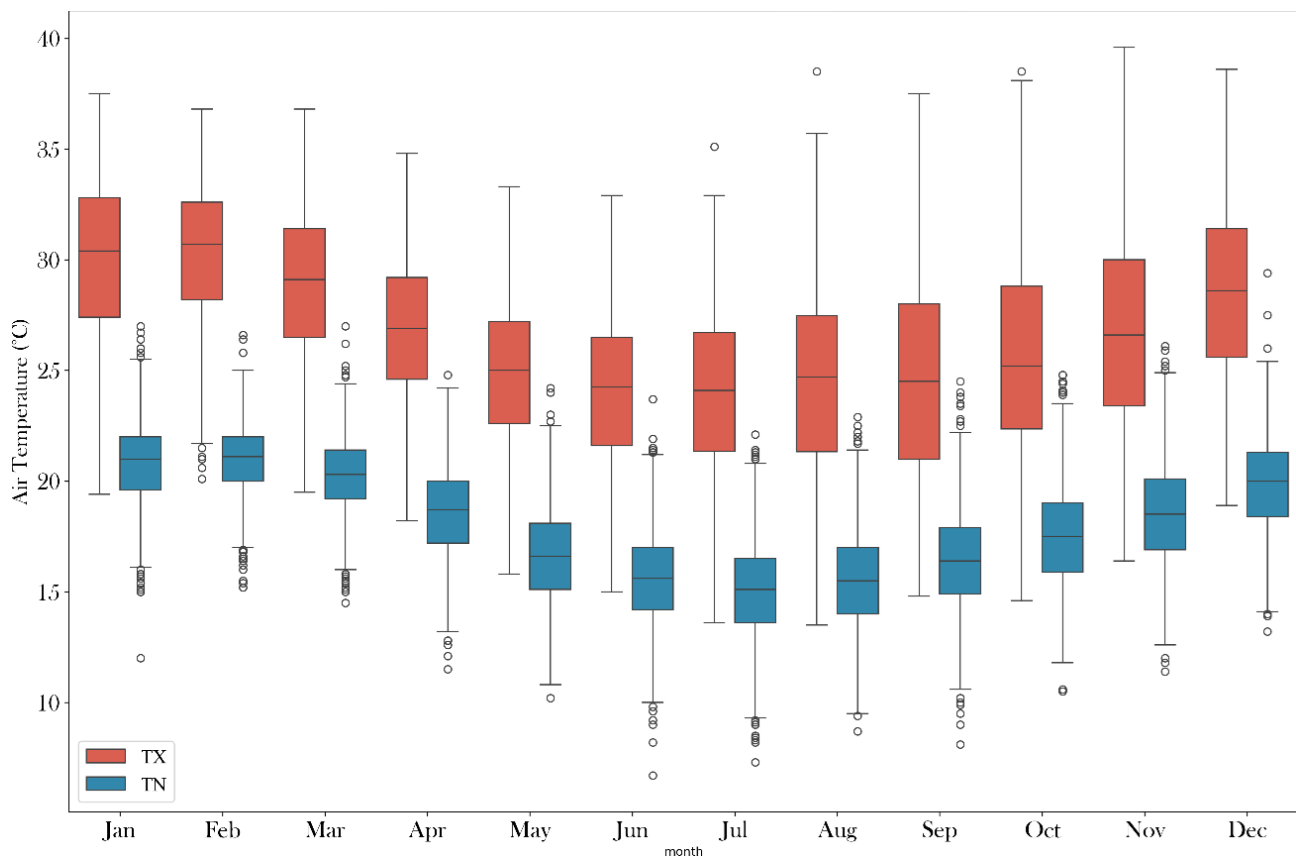


Figure 2 Boxplots of TXmean (°C in red) and TNmean (°C in blue) at ABVI (1) in the period 1991-2020. The “box” consists of minimum, maximum, first quartile (Q1), second quartile or median (Q2), and third quartile (Q3) of data distributions. The outliers (circles) are classified as values lower than $(Q1 - 1.5 \text{ IQR})$ and higher than $(Q3 + 1.5 \text{ IQR})$, where $\text{IQR} = Q3 - Q1$.

the coast, breezes predominate from the south during the afternoon and evening, the sea breeze, and from the north during dawn and morning, the land breeze (Pimentel et al. 2014). The thermal difference between the continent and the ocean creates an atmospheric pressure gradient, thus generating breezes. In spring and summer, when the warming of the land is more intense, the temperature gradient between the ocean and the land intensifies the circulation of sea breezes, thus increasing the frequency of southerly winds compared to the annual pattern. In autumn and winter, winds from the south are less frequent (they occur predominantly during the passage of transient systems), and winds from the north increase in frequency (Dereczynski et al. 2013).

The relief of Rio de Janeiro significantly affects the rainfall in the city, with maxima concentrated in the surroundings of the three massifs (Dereczynski et al. 2009). In the lower lands of the North and West Zones of the city, the annual rainfall totals are around 1,200 mm, while in the Tijuca massif, this value is almost double, around 2,200 mm. This spatial distribution of rainfall volumes is explained

by the displacement of meteorological systems, mainly from south to north, producing maximum (minimum) precipitation windward (leeward) of the mountains. The orographic ascent of humid air advected by the sea breeze strengthens this process (Luiz-Silva & Oscar-Júnior 2022). Studies that analyzed extreme precipitation events (accumulated over 30 mm/day) indicate that in 77% of cases, these volumes are caused by the passage of frontal systems (Pristo et al. 2018).

The spatial distribution of air temperature in Rio de Janeiro is also influenced by the same physiographic aspects, i.e., the topography and the land-sea breeze (Neiva et al. 2017). The Tijuca and Pedra Branca massifs, located close to the seafront, make it difficult for sea breezes and transient systems to penetrate the interior of the city, thus making the North (where the Nilton Santos Olympic Stadium is located) and West Zones of the city hotter and drier than the South Zone. In addition, the land breezes (hotter and drier) help to increase the maximum temperature in the North and West Zones.

3.1.1 Temperature Extreme Trends

The highest annual values of TX (TXx) increased from 36.1 °C to 36.8 °C between the end of the 20th century and the beginning of the 21st century (see Table 3). On the other hand, the highest annual of TN (TNx) showed a decrease from 25.3 °C to 24.8 °C. This possibly indicates the reduction of the forested area in the city (Nehren et al. 2013), which allows greater absorption of radiation during the day but also more significant loss at night due to the reduction of local humidity. The days in the year equal to or over 30 °C (SU30) showed a sharp increase between 1981 and 2020, from an average of 78 days to 85 days.

Figure 3 shows the trends in the annual number of hot days (TX90p) and hot nights (TN90p) in ABVI (1) between 1967 and 2023. TX90p (TN90p) is computed by the number of days in the year when TX (TN) exceeds the 90th percentile of climatology. There is a statistically significant increase in such indicators of temperature extremes in Rio de Janeiro. In the late 1960s and 1970s, the number of hot days (TX90p) and hot nights (TN90p) in Rio de Janeiro was around 30 days. In the 2010s and

early 2020s, this number has already reached about 60 days, thus evidencing the city’s warming over the last decades. Such temperature extremes directly impact human health, the environment, and even various economic activities (Pinkerton & Rom 2021).

3.1.2 Temperature Extremes in November

Figure 4 shows November’s TXmean and TNmean anomalies in ABVI (1) between 1967 and 2023. It is observed that from the 1980s onwards, the frequency of occurrence of positive TXmean and TNmean anomalies has increased.

The frequencies of occurrence of TN above 20 °C (TR20), TX above 30 °C (SU30), and the duration of the heat waves (WSDI) that occurred in November at ABVI (1) between 1967 and 2023 are shown in Figure 5. As WSDI requires at least 6 consecutive days with TX above its 90th percentile, it is zero when the period is shorter than 6 days. Using the definition presented in Table 1, the November 2023 heat wave extended from November 11 to November 18, an 8-day heat wave. As expected, it

Table 3 TXx (°C), TNx (°C) and SU30 (days) mean and standard deviation in the periods 1981-2000 and 2001-2020.

Temperature Extreme Indices (Unit)	Mean [Standard Deviation]	
	1981-2000	2001-2020
TXx (°C)	36.1 [1.2]	36.8 [1.3]
TNx (°C)	25.3 [1.7]	24.8 [1.8]
SU30 (days)	78 [27]	85 [24]

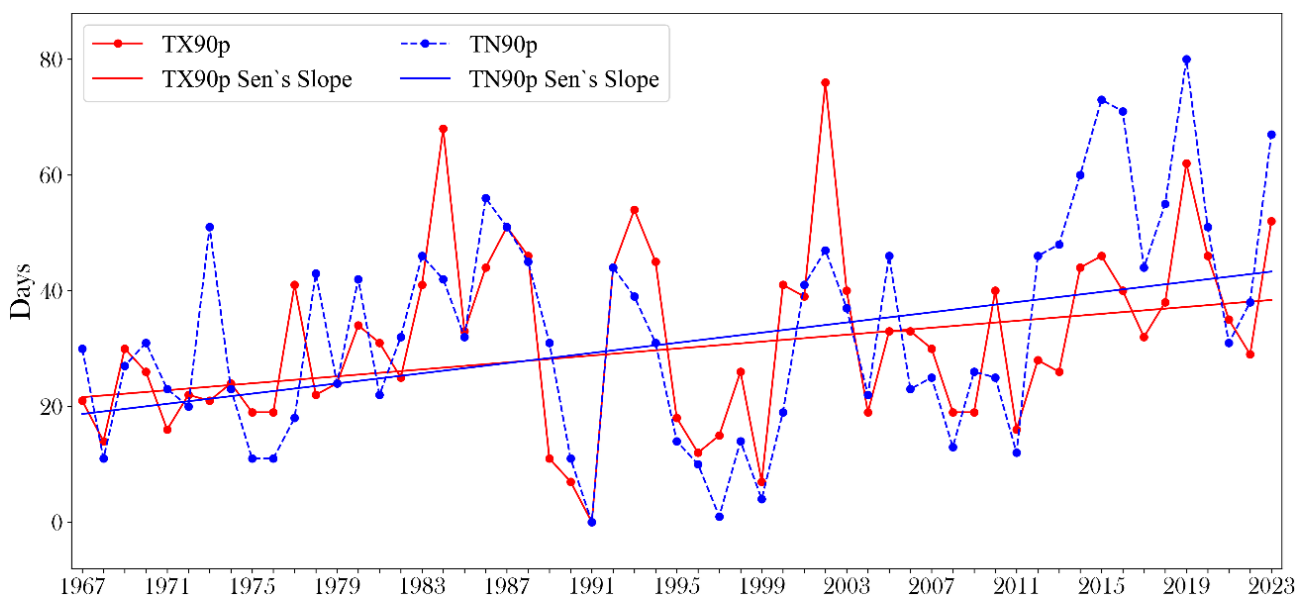


Figure 3 Annual number of hot days (TX90p; in days) and hot nights (TN90p; in days) at ABVI (1) from 1967 to 2023.



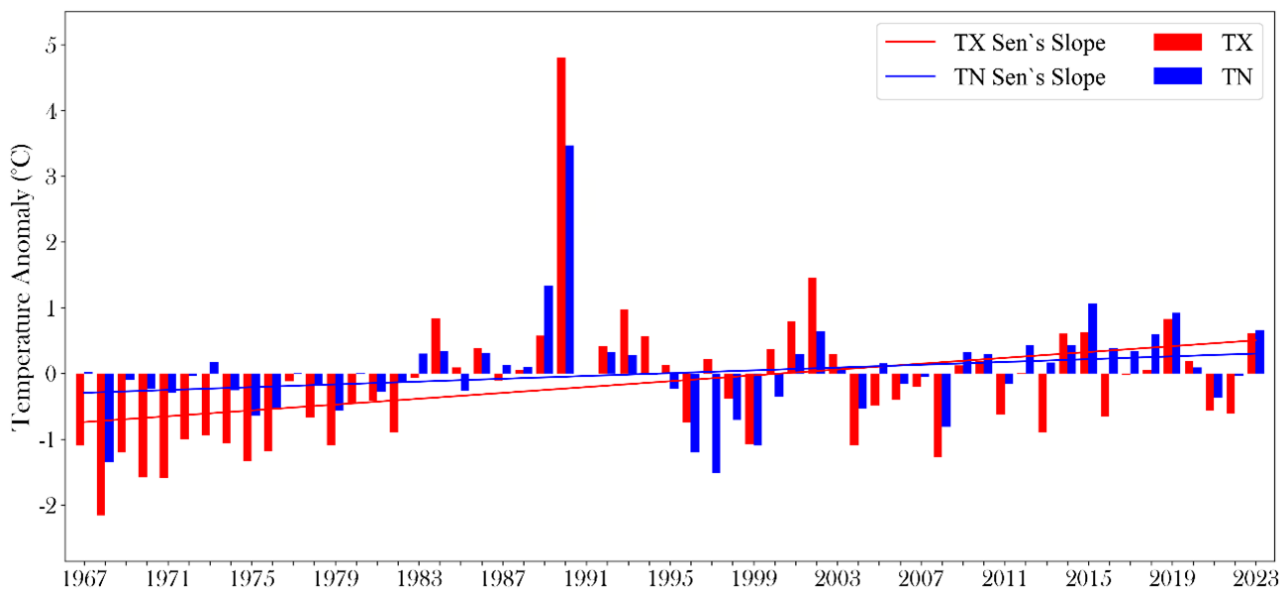


Figure 4 Anomalies, relative to 1991-2020 November’s climatology, of TXmean (red bars) and TNmean (blue bars), at ABVI (1) for the period November/1967-November/2023, except for November/1991, where data is missing.

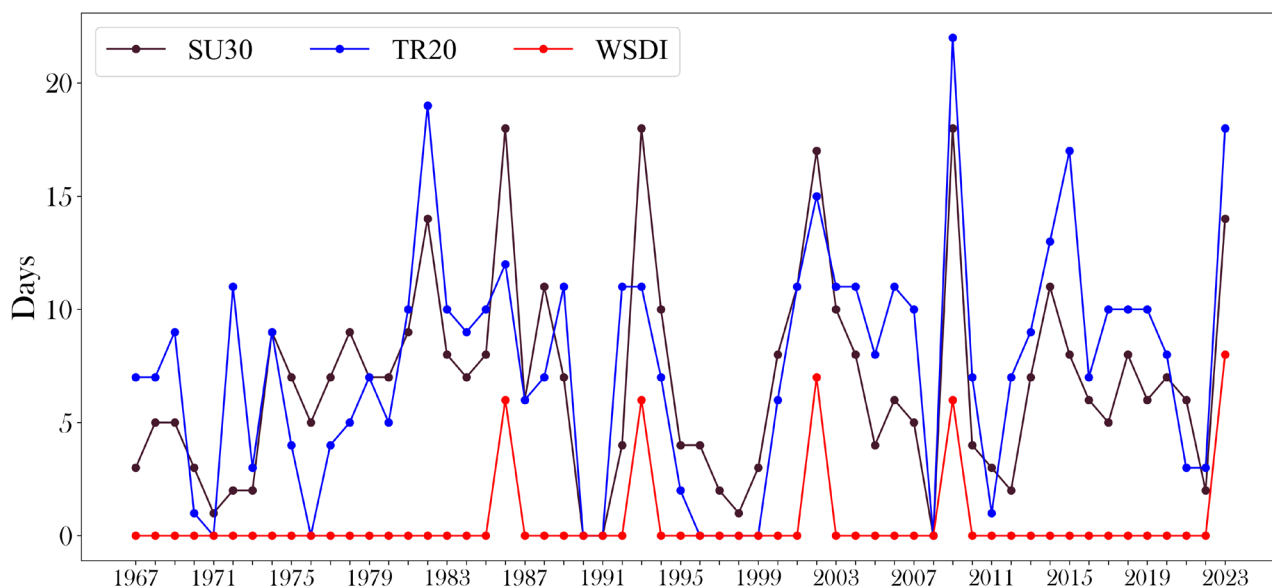


Figure 5 TR20 (days), SU30 (days), and WSDI (days) in November at ABVI (1) from 1967 to 2023.

is observed that these two curves (TR20 and SU30) are mostly positively correlated, i.e., in years in which there are several days of high TN, there are also several days with high TX, reflecting an increase in TR20 and SU30. The highest TR20, and SU30 years in Rio de Janeiro were 1982, 1986, 1993, 2002, 2009, and 2023, all El Niño years, except 1993, a neutral year. This result agrees with Grimm (2003), which states that El Niño events cause drier and warmer austral springs (SON), mainly in November, in

most of central-east Brazil. Positive temperature anomalies and negative precipitation anomalies are observed in most of Southeast Brazil in November 2023 and also in SON 2023 (figures not shown).

Figure 5 also shows that in 2023, almost 20 days in November recorded TN above 20 °C and that half of the month recorded TX above 30 °C, in addition to the maximum recorded of eight consecutive days with TX above its 90th percentile. The last day of the November



2023 heat wave, established between November 11 and 18, coincided with the second day of the massive gathering concert in Rio de Janeiro. The heat waves that hit Brazil between September and November 2023 caused heat stress in a significant portion of the population, including Rio de Janeiro.

Geirinhas et al. (2020) showed that, between 2000 and 2015, the leading causes of death from excessive heat in the Metropolitan Region of Rio de Janeiro were circulatory diseases and respiratory problems. The situation tends to be increasingly worrying since the frequency of hot nights has increased significantly over the last decades (Luiz-Silva et al. 2023), as shown in Figure 3.

TXmean and TNmean for November in seven stations in Rio de Janeiro are presented in Figure 6 for 2001-2023. On average, considering the seven meteorological stations, TXmean is around 28 °C, while TNmean settles around 21 °C. The ABVI (1) exhibits the lowest values (19 °C to 27 °C) due to its location in a higher region (347 meters) and with vegetation cover (Atlantic Forest). The hottest stations are SBJR (6) and SCRIS (12), located in the West and North zones of the city, respectively, and both have urban density and are further away from the ocean. SCRIS (12) is the closest weather station to the Nilton Santos Olympic Stadium (about 10 km) and exhibits TXmean and TNmean averages in 2001-2023 of 30 °C and 22 °C, respectively.

It is observed that 2009 and 2023 were the years with the hottest November in the data series. In these years, there was the influence of El Niño, and in several stations in the

city of Rio de Janeiro, TXmean oscillated between 32 °C and 34 °C, while TXmean was between 23 °C and 25 °C. In equatorial and tropical regions, heat wave episodes may be associated with the El Niño phenomenon, especially during spring and summer (Cai et al. 2020; Coelho et al. 2012; Geirinhas et al. 2018).

3.2 The Heat Wave Event

3.2.1 Synoptic Analysis

The Southeast region of Brazil is, for most of the time, under the action of SASH. This system is responsible for light winds from the north and east directions, subsidence preventing the development of deep convective clouds, mild temperatures, and reduced precipitation. This stability situation generated by SASH is interrupted by the passage of transient systems, with frontal systems being the most frequent (Dereczynski et al. 2009; Escobar et al. 2019; Satyamurty et al. 1998).

Frontal systems cause significant changes in weather conditions. Cold fronts, where the cold air mass displaces the warm air mass on the surface, are identified by analyzing surface synoptic charts and satellite images. They generally move from southwest to northeast over the continent and the adjacent Atlantic Ocean (Andrade 2005). In general, before the entry of a frontal system in Rio de Janeiro, the MSLP is reduced, the temperature rises, and the wind, coming from the north quadrant, intensifies.

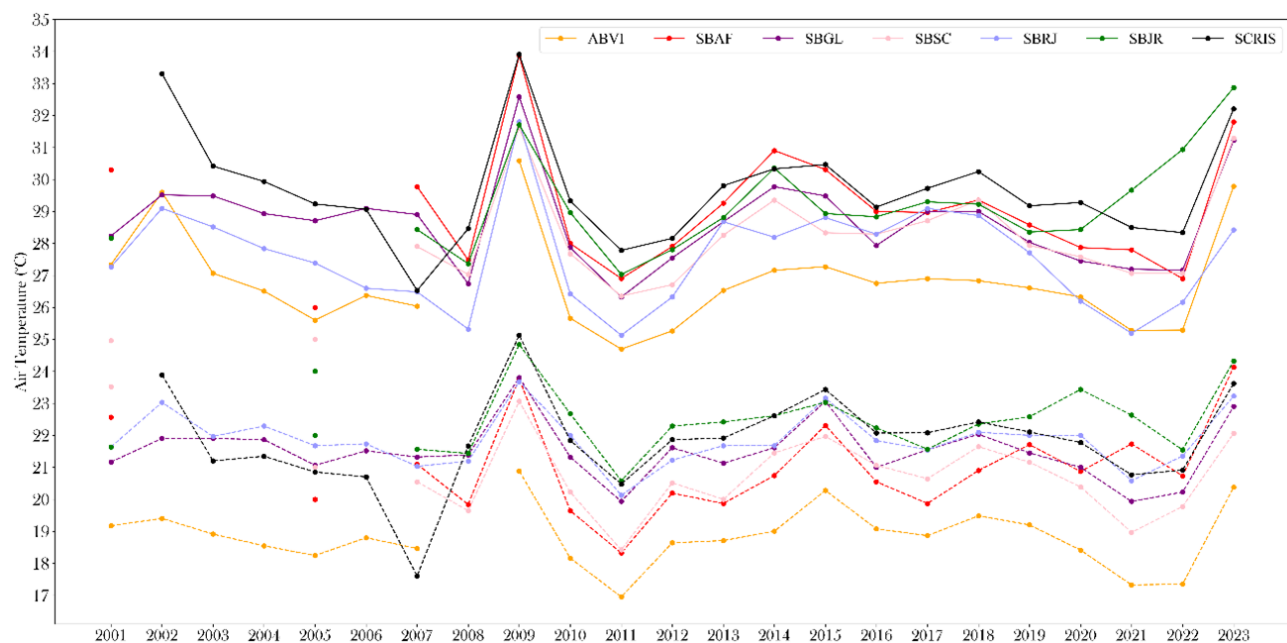


Figure 6 TXmean and TNmean (°C) in November of seven meteorological stations in Rio de Janeiro (ABVI (1), SBAF (2), SBGL (3), SBSC (4), SBRJ (5), SBJR (6) and SCRIS (12)) during 2001-2023. Full (dotted) lines referring to TXmean (TNmean).



During the passage of a cold front, the wind weakens and turns south; then it becomes stronger, with gusts (Dereczynski et al. 2019). Convective clouds form mainly in the wet season, and rain and thunderstorms often occur. After the passage of cold fronts, the post-frontal migratory anticyclone causes milder temperatures, reduced humidity, and higher atmospheric pressure, promoting clear skies with few clouds, good visibility, and calm winds.

An average of 2.8 frontal systems in November passes over Rio de Janeiro (Bonnet et al. 2018). During November 2023, three frontal systems (days 4, 18, and 24) passed through Rio de Janeiro, indicating that no type of blocking could prevent or reduce the number of transient systems through the study area.

Figure 7 shows the MSLP fields and the satellite images from November 13-18, 2023, at 21:00 LT. Figure 8 shows the São Cristóvão station time series for November 13-20, 2023.

On the night of November 13 (Figure 7A), it is possible to observe a frontal system in the South Region of Brazil, associated with an extratropical cyclone of 980 hPa at approximately 50°S/40°W. The following day, November 14 (Figure 7B), the displacement of this frontal system to the north and with greater organization was observed. Over Rio de Janeiro, convective clouds were observed. Thus, between the night of the 14 and the early morning of November 15, moderate rain, thunderstorms, and strong winds occurred in the city's surroundings, mainly in the West Zone. The total precipitation in approximately 12 hours reached its maximum at SCRIS (12) (37.4 mm), which can be seen in Figure 8, where a peak of very intense rainfall (10.4 mm/15 min) occurred between 22:45 LT and 23:00 LT on November 14. Associated with the formation of this convective cloud formation, a slight drop in TX and TN was observed over the city. In SCRIS (12) (Figure 8) on November 15, TX (35.2 °C) and TN (24.8 °C) were reduced by approximately 1 °C compared to the previous day (November 14).

From November 15 (Figure 7C) until November 17 (Figure 7E), this frontal system oscillated, retreating to the south and advancing to the north, characterizing a prefrontal situation in Rio de Janeiro. Finally, on the evening of November 18 (Figure 7F), this frontal system moved northward. The approach of the front contributed to an increase in TX and TN, as well as a reduction in MSLP and RH, which occurred throughout the city. During the passage of the frontal system over the city, which occurred around 19:00 LT on November 18, light rain, thunderstorms, and wind gusts were observed. After its passage, the air temperature dropped sharply.

In SCRIS (12) (Figure 8), the TX reached 41.0 °C on November 18 at 14:45 LT and dropped to 30.3° C on November 19 (2:15 LT), a drop of 10.7 °C. The TN of 29 °C, observed at 4:15 LT on November 18, dropped to 23.9 °C on November 19 at 21:45 LT. The MSLP reached a minimum value (998 hPa) on November 18 and then rose again. The RH reached very low values (33% on the afternoon of November 16) but rose on November 17 and 18, worsening the heat sensation. The wind speed on November 17 and 18 did not exceed 10 m/s, and then, at the time of the cold front arrival, it reached 29.3 m/s (82° direction) at 20:00 LT on November 18, reducing after that. The precipitation associated with the cold front passage was not very intense, with the highest accumulation observed in JPA (14), with 43.4 mm, between November 19 and 20.

Although the approach of a cold front in Rio de Janeiro on the night of November 14 caused isolated rains and strong winds, mainly in the city's West Zone, only a drop of 1 °C on November 15 was observed in TX and TN, relative to the previous day. During the 15th and 17th of November, this same frontal system remained undulating, retracting to the south and advancing to the north, contributing to the increase in air temperature in such a pre-frontal situation. On November 19, after the passage of this frontal system, the heat wave, already on its eighth day, ended.

3.2.2 The Extreme Maximum Temperature

The highest TX recorded in the city was 43.5 °C at GBA (9) on November 18. This value is higher than all the TXs observed in 66 State of Rio de Janeiro stations in different periods between 1909 and 2009 (INMET 2010). The previous highest TX in the city was 43.1 °C recorded at Bangu station (1922-2004) on January 14, 1984.

The analysis of the longest data series in the city, with 57 years (1967-2023), ABVI (1) revealed that the temperature of 39.6 °C observed on November 18 was the highest value ever recorded in the entire series. This TX value is 11.9 °C higher than its November climatology (1991-2020). The TN of ABVI (1) did not rise as much as the TX, reaching 24.9 °C on November 18, a value 6.2 °C higher than the TN climatology for November.

Analyzing all air temperature time series at the city's five airports in all months in the period 2001-2023, it can be observed that the maximum temperatures that occurred in the week of the event (Table 4) were the highest values ever recorded (except at SBRJ (5)). At SBSC (4) and SBJR (6), maxima of 40 °C and 42 °C were also observed on several other dates. It is important to highlight that TXs equal to or

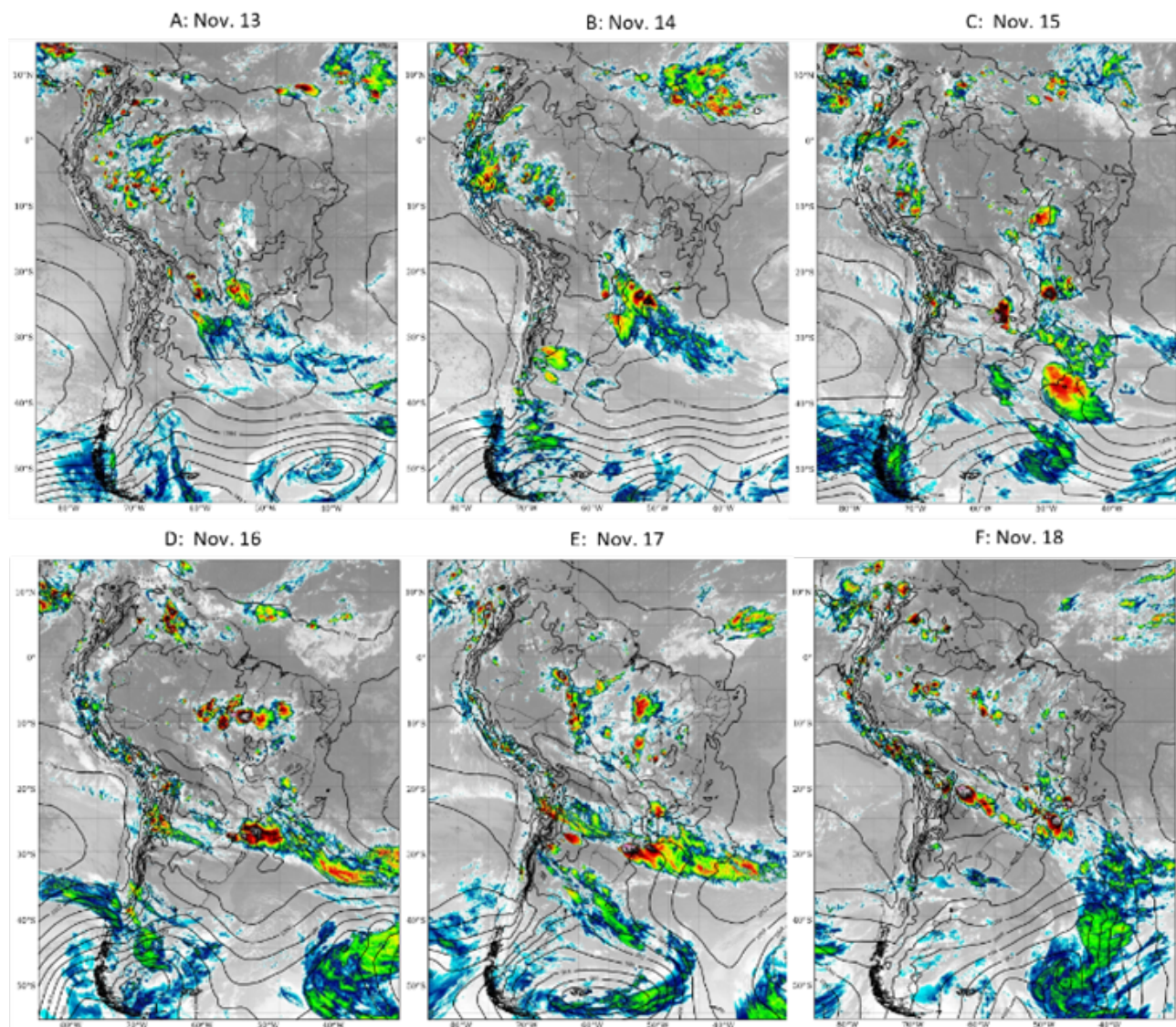


Figure 7 MSLP contours (every 4 hPa) and GOES 16 satellite images in the infrared channel (Channel 14) for 21:00 LT: A: November 13; B: November 14; C: November 15; D: November 16; E: November 17; and F: November 18, 2023.

over 40 °C were recorded in the city since November 16, as seen in Table 4 for SBJR (6) (TX of 42 °C).

Considering the November climatology (2001-2020) of TX from Rio de Janeiro airport stations, it is observed that on November 18, 2023: i) at SBAF (2) TX was 13.5 °C higher than its climatology (28.5 °C); ii) at SBGL (3) TX was 13.1 °C above its climatology (27.9 °C); iii) at SBSC (4) TX was 11.7 °C higher than its climatology (27.3 °C); iv) at SBRJ (5) TX was 7.3 °C higher than its climatology (26.7 °C), and v) at SBJR (6) TX was 7.5 higher than its climatology (28.5 °C). Regarding the November climatology (1991-2020) of ABVI (1), TX was 12.5 °C higher than its climatology (27.1 °C).

The air temperature diurnal cycles of November 17 and 18 are compared to the mean November diurnal cycle (2001-2020) for SBGL (3) in Figure 9. The climatological mean diurnal temperature cycle shows a minimum at 5:00 LT and a maximum at 13:00 LT. In general, TX occurs about 3 hours after the maximum incidence of solar radiation, around 15:00 LT. The early maximum, around 13:00 LT or 14:00 LT, in SBGL (3) may be associated with the entry of the sea breeze, which occurs between 12:00 and 14:00 LT (Martins 2012).

It can be seen from Figure 9 that on November 17 and 18, TN (TX) occurred between 1:00 LT and 6:00 LT (at noon LT), and around 5 to 6 °C (13 °C) warmer than its climatology.

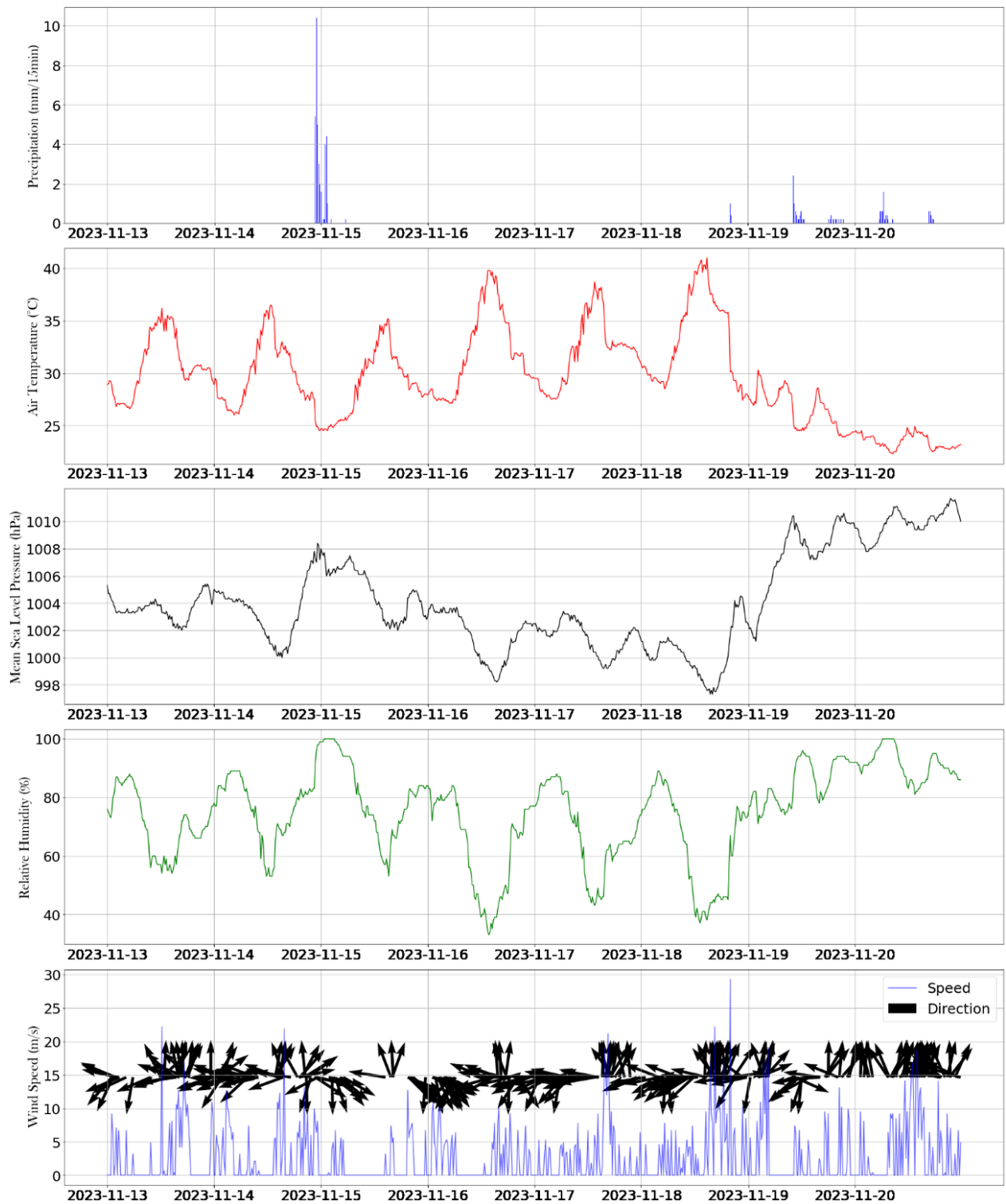


Figure 8 SCRIS (12) for the period from November 13-20, 2023, containing data every 15 minutes: accumulated precipitation (mm/15 min), air temperature (°C), mean sea level pressure (hPa), relative humidity (%), wind speed (m/s), and wind direction (degrees).



Table 4 Highest TX in the period 2001-2023, recorded at airports in the city of Rio de Janeiro. Dates in bold refer to dates during the week of the heat wave event that occurred in November 2023.

Airport Station	Highest TX and dates
SBAF (2)	42 °C – 11/18/2023
SBGL (3)	41 °C – 11/18/2023
SBSC (4)	40 °C – 09/19/2012, 11/12/2013, 10/13/2014, 10/15/2015, 01/03/2019, 09/12/2019, 09/27/2020, and 11/17/2023
SBRJ (5)	41 °C – 11/12/2013
SBJR (6)	42 °C – 01/29/2021, 10/27/2022, 01/03/2023, and 11/16/2023

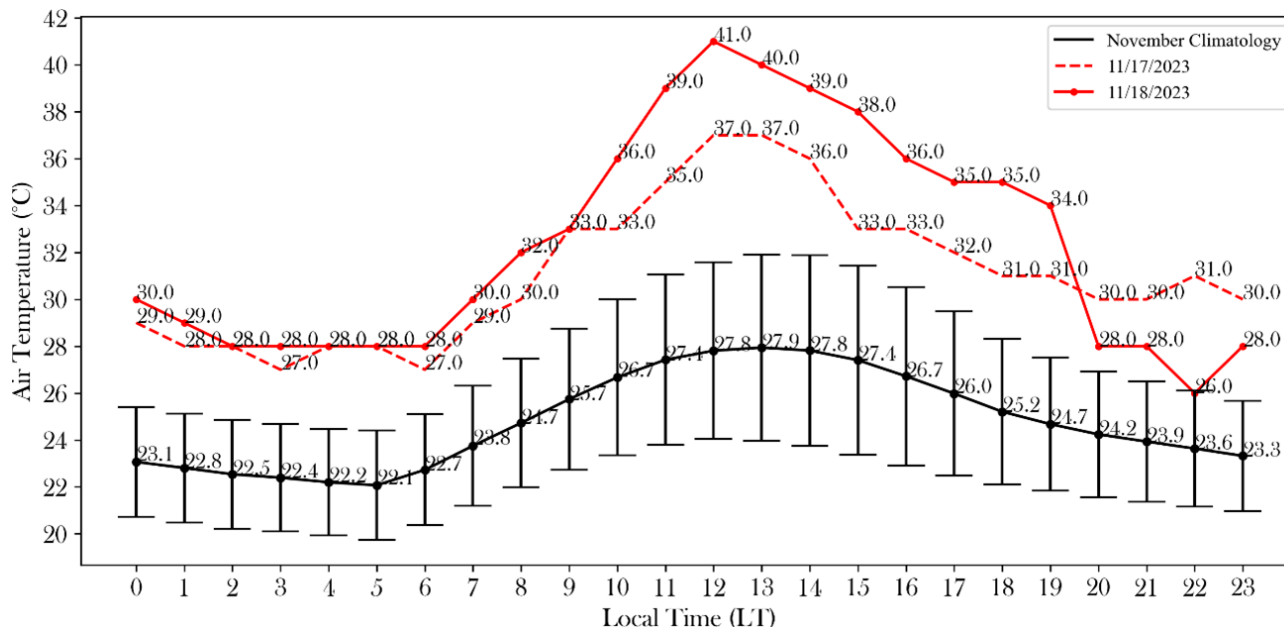


Figure 9 November climatological (2001-2020) hourly air temperature (°C) and hourly temperature on November 17 and 18, 2023 at SBGL (3). The bars represent the standard deviations of the climatological series.

Thus, on November 17 and 18, the air temperature was high throughout the day, increasing the thermal discomfort.

On November 18, TX varied between 31.9 °C at COPA (13) and 43.5 °C at GBA (9). Eleven weather stations registered TX equal or over 40.0 °C: ABVA (11) – 40.1 °C; JPA (14) – 40.3 °C; BRC (8) – 40.3 °C; SC (10) – 40.8 °C; SBJR (6) – 41.0 °C; SCRIS (12) – 41.0 °C; SBGL (3) – 41.0 °C; MAR (16) – 41.4°; VMIL (15) – 41.6 °C; SBAF (2) – 42.0 °C, and GBA (9) – 43.5 °C. Even at ABVI (1) and ABVA (11), the coldest area of the city, the TXs were relatively high, respectively 39.6 °C and 40.1 °C. Among the 16 weather stations, just in five of them, TX was under 40.0 °C: COPA (13) – 31.9 °C; SBRJ (5) – 34.0 °C; JBOT (7) – 38.3 °C, SBSC (4) – 39.0 °C, and ABVI (1) – 39.6 °C. Unfortunately, the Irajá weather station, closest to the Nilton Santos Olympic Stadium, was under maintenance during the week of the concert.

3.2.3 Heat Index and Thermal Discomfort Index

Figure 10 shows the HI (°C) calculated from T and RH and TDI for November 17 and 18, 2023, at SBJR (6). On November 17, 2023, TDI ranged between class 4 and class 5. On November 18, 2023, early in the morning (8:00 LT), TDI class 6 had already been reached, corresponding to the “state of medical emergency” due to extreme discomfort that can cause heat stroke. This “medical emergency” class prevailed from 8:00 LT until 11:00 LT and from 13:00 LT until 15:00 LT, and peaked between 14:00 LT and 15:00 LT when the HI reached 55.1 °C. Therefore, in addition to a very high HI, the number of hours of exposure, seven hours, was also high, which must have caused prolonged thermal stress in the population.



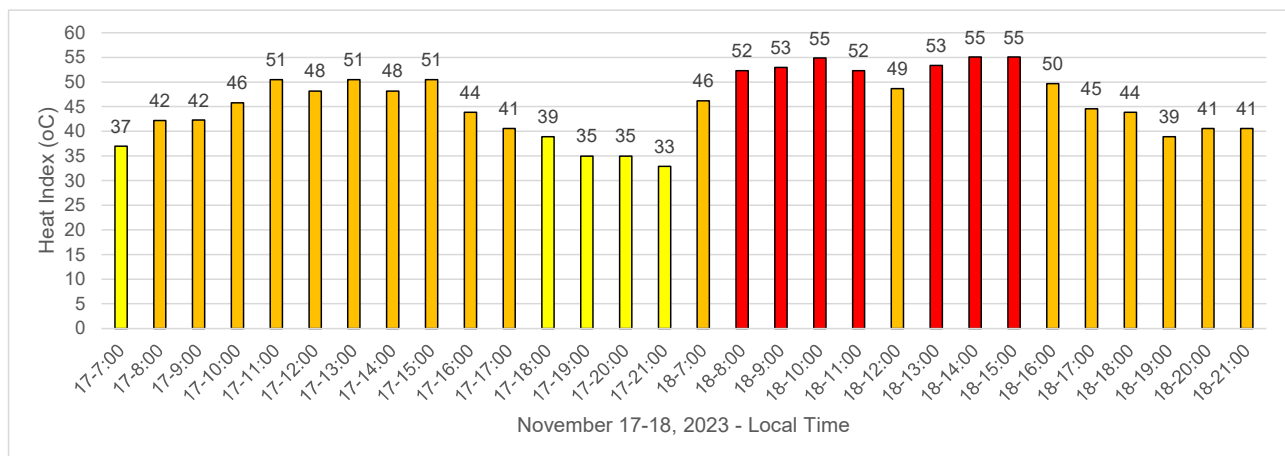


Figure 10 Heat Index (°C) calculated for SBJR (6) on November 17 and 18, 2023 (from 7:00 to 23:00 LT). The colors of the bars correspond to the classes 4 (yellow), 5 (light orange), and 6 (red) of the Thermal Discomfort Index – TDI (see Figure SM1).

4 Conclusions

This article analyzes the weather conditions in the city of Rio de Janeiro associated with the heat wave that occurred during the concert of the American singer Taylor Swift on November 17 and 18, 2023. The objective is to answer the question: Can the high temperatures recorded in Rio de Janeiro on November 17 and 18, 2023, be considered an extreme weather event?

In the climatological analysis, it was observed that extreme heat events have been increasingly frequent and intense in the city of Rio de Janeiro over the last few years, especially during El Niño years and in the spring and summer seasons. Indices that evaluate the highest maximum temperatures recorded in the year and the number of days with temperatures above 30 °C have shown an increase over the last few decades. The city's extremely hot days and nights practically doubled between the 1970s and 2010s. Specifically for November, it was found that TX_{mean} was 30 °C, but with frequent occurrences exceeding 35 °C, as occurred in the year 2023. ABVI (1) reached almost 40 °C on November 18, 2023, on the last day of a heat wave that lasted eight consecutive days, from November 11 until 18, 2023. This high TX value (39.6 °C) was 12.8 °C higher than its climatology (1991-2020) for November. In addition to the heat wave, the El Niño phenomenon was also configured in the Pacific Ocean from April 2023 to May 2024. In most of Southeast Brazil, during El Niño years, springs are generally drier and warmer, as observed in November 2023.

Analyzing the events since the beginning of the week's concert, November 13, it is verified that even with the approach of a cold front over Rio de Janeiro on

November 15, with a slight reduction in TX and TN, the TX values remained very high, above their 90th percentile, characterizing the heat wave that lasted eight days. TN continued to rise during the week but with less extreme values than those recorded in TX. On November 18, with the approach of this same frontal system, TXs exceeded 40 °C in 11 meteorological stations in the city, reaching 43.5 °C at GBA (9). The HI on November 18 at SBJR (6) reached 55.1 °C. Since 8:00 LT on November 18, the values of TDI already indicated a state of medical emergency. In addition, the wind was also predominantly weak, aggravating the feeling of heat. In this situation, thousands of people remained in line to attend the singer's concert, which was postponed only earlier on November 18.

Therefore, it is concluded that the heating event in Rio de Janeiro on the first two days of the concert, on November 17 and 18, was an extreme meteorological event. This event was caused by a heat wave in a pre-frontal situation, during an El Niño period, and in the context of global warming. Such heat waves pose a significant risk to human health and are potentially lethal, as proven by the death of a young student on the first day of the concert.

In Brazil, unfortunately, in most cases that precede a catastrophe, the action of the public agencies responsible for protecting the population is usually late, acting much more in response than in prevention. It is evident that, even for non-specialists, in a situation where a large number of people are long exposed to intense heat, the prohibition by the event organizers of the entry of bottles of water by spectators is entirely absurd. This vacuum in the legislation was only corrected the day after the student's death through the Ordinance of the Ministry of Justice and

Public Security No. 35 of November 18, 2023 (MJSP 2023). In this ordinance, it was established, among other things, that the companies responsible for the production of the events must guarantee free access to bottles for personal use containing water for consumption at the event and must provide drinking fountains or distribute packages with water suitable for consumption, through the installation of “hydration islands” at no additional cost to the consumer.

Subsequently, on June 28, 2024, the City Hall of Rio de Janeiro published Decree No. 54740 (Prefeitura do Rio de Janeiro 2024), classifying Heat Levels (HL) for defining municipal action protocols. HLs are considered through the relationship between the HI and the heat exposure time. This decree defines heat waves as three consecutive days with HI over 36°C to 44°C for at least four hours a day or over 44°C for at least two hours. In HL5 (record of extreme heat indices with a forecast of permanence or increase by at least three consecutive days), activities at risk for extreme heat that are not adapted to face the heat wave may be interrupted, seeking to preserve the population from the impacts of heat waves.

It is worth pointing out that although the focus of this article was the case study of a heat wave that occurred during a concert held inside a stadium, any outdoor activity needs to be scheduled respecting the local atmospheric conditions. Thus, work activities carried out in outdoor areas, sports activities, concerts with a large concentration of audiences, where people are exposed to solar radiation, in environments without adequate cooling or shading, should be avoided at the hottest times of the day and even interrupted depending on the expected heat index forecasted.

5 References

- Alvares, C.A., Satepe, J.L., Sentelhas, P.C., Gonçalves, J.L.M. & Sparovek, G. 2014, ‘Köppen’s climate classification map for Brazil’, *Meteorologische Zeitschrift*, vol. 22, no. 6, pp. 711-728. DOI: 10.1127/0941-2948/2013/0507
- Andrade, K.M. 2005, ‘Climatologia e Comportamento dos Sistemas Frontais sobre a América Do Sul’, Master’s dissertation, Instituto Nacional de Pesquisas Espaciais, Programa de Pós-graduação em Meteorologia. https://bdtd.ibict.br/vufind/Record/INPE_ba69c53bee014a9b31651b4f77f8eb36
- AP News. 2023, ‘Taylor Swift’s Brazil tour marred by deaths and a dangerous heat wave’, viewed August 13, 2024, <<https://apnews.com/article/taylor-swift-concert-brazil-rio-eras-tour-713f3e0051d60c4f280f1f3b242b1569>>.
- Bonnet, S.M., Dereczynski, C.P. & Nunes, A. 2018, ‘Caracterização Sinótica e Climatológica de Eventos de Chuva Pós-Frontal no Rio de Janeiro’, *Revista Brasileira de Meteorologia*, vol. 33, no. 3, pp. 547-557, DOI: 10.1590/0102-7786333013
- Cai, W., McPhaden, M.J., Grimm, A.M., Rodrigues, R.R. et al. 2020, ‘Climate impacts of the El Niño-Southern Oscillation on South America’, *Nature Reviews Earth & Environment*, vol. 1, pp. 215-231, DOI: 10.1038/s43017-020-0040-3
- Cavalcanti, I.F.A.; Ferreira, N.J.; Justi da Silva, M.G.A. & Silva Dias, M.A.F. 2009, ‘Tempo e Clima no Brasil’, Oficina de Textos, First edition.
- Coelho, C.A.S., Cavalcanti, I.A.F., Costa, S.M.S., Freitas, S.R. et al. 2012, ‘Climate diagnostics of three major drought events in the Amazon and illustrations of their seasonal precipitation predictions’, *Meteorological Applications*, vol. 19, no. 2, pp. 237-255, <https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/met.1324>
- Dereczynski, C.P., Oliveira, J.S. & Machado, C.O. 2009, ‘Climatologia da Precipitação no Município do Rio de Janeiro’, *Revista Brasileira de Meteorologia*, vol. 24, no. 1, pp. 24-38, DOI: <https://doi.org/10.1590/S0102-77862009000100003>
- Dereczynski, C.P., Marengo, J.A., Justi, M.G.A. & Santos, I. 2011, ‘Região Metropolitana do Rio de Janeiro Vulnerabilidade das Megacidades Brasileiras às Mudanças Climáticas’, *Projeto Megacidades, Vulnerabilidade e Mudanças Climáticas*, Rio de Janeiro, pp. 1-31, https://rio.rj.gov.br/dlstatic/10112/2122393/DLFE-232588.pdf/mapa_vulnerabilidade_inpe_smac.pdf
- Dereczynski, C.P., Luiz-Silva, W. & Marengo, J. 2013, ‘Detection and projections of climate change in Rio de Janeiro, Brazil’, *American Journal of Climate Change*, vol. 2, no. 1, pp. 25-33, https://www.scirp.org/pdf/AJCC_2013032715394029.pdf
- Dereczynski, C.P., Lopes, I.R., Carvalho, N.O., Justi da Silva, M.G.A., Grossmann, K.S. & Martins, R.P. 2019, ‘Climatology of Espírito Santo and the Northern Campos Basin, Offshore Southeast Brazil’, *Anuário do Instituto de Geociências*, vol. 42, no. 1, pp. 386-401.
- Escobar, G.C.J., Reboita, M.S. & Souza, A. 2019, ‘Climatology of surface baroclinic zones in the coast of Brazil’, *Atmosfera*, vol. 32, pp. 129-141, DOI: 10.20937/ATM.2019.32.02.04
- Fanger, P.O. 1970, ‘Thermal Comfort’. New York: Mc Graw-Hill Book Company, INTERNATIONAL ORGANIZATION FOR STANDARDSIZATION, Ergonomics of the thermal environment Assessment of the influence of the thermal environment using subjective judgement scales, ISO 10551, Geneva, 1995.
- Frich, P., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A.M.G. & Peterson, T. 2002, ‘Observed coherent changes in climatic extremes during the 2nd half of the 20th century’, *Climate Research*, vol. 19, pp. 193-212, <https://www.int-res.com/articles/cr2002/19/c019p193.pdf>
- Geirinhas, J.L., Trigo, R.M., Libonati, R., Coelho, C.A.S. & Palmeira, A.C. 2018, ‘Climatic and synoptic characterization of heat waves in Brazil’, *International Journal of Climatology*, vol. 38, no. 4, pp. 1760-1776, DOI: 10.1002/joc.5294
- Geirinhas, J.L., Russo, A., Libonati, R.M., Castro, L.C.O., Peres, L.F., Magalhães, M.A.F.M. & Nunes, B. 2020, ‘Heat-related mortality at the beginning of the twenty-first century in Rio de Janeiro, Brazil’, *International Journal of Biometeorology*, vol. 64, pp. 1319-1332, DOI: 10.1007/s00484-020-01908-x.
- Grimm, A. M. 2003, ‘The El Niño Impact on the Summer Monsoon in Brazil: Regional Processes versus Remote Influences’, *J. Climate*, vol. 16, pp. 263-280, DOI: 10.1175/1520-0442(2003)016<0263:TENIOT>2.0.CO;2.

- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. & Thépaut, J. 2020, 'The ERA5 global reanalysis', *Quarterly Journal of the Royal Meteorological Society*, vol 146, no. 730, pp. 1999-2049, DOI: 10.1002/qj.3803
- Instituto Nacional de Meteorologia – INMET. 2010. CD with monthly and annual extremes of maximum and minimum temperature, highest precipitation in 24 h, and highest monthly accumulated rainfall for 66 stations of the Sixth Meteorology District in the State of Rio de Janeiro. Rio de Janeiro, RJ.
- INMET 2023. Inmet emite alerta para onda de calor nos próximos dias. Viewed 19 July 2024.
- IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32, DOI: 10.1017/9781009157896.001. Karl, T.R., Nicholls, N. & Ghazi, A. 1999, 'CLIVAR/GCOS/WMO workshop on indices and indicators for climate extremes: Workshop summary', *Weather and Climate Extremes*, vol. 42, pp. 3-7, DOI: 10.1007/978-94-015-9265-9_2.
- Luiz-Silva, W. & Dereczynski, C.P. 2014, 'Climatological Characterization and Observed Trends in Climatic Extremes in the State of Rio de Janeiro', *Anuário do Instituto de Geociências*, vol. 37, no. 2, pp. 123-138, <https://revistas.ufjf.br/index.php/aigeo/article/view/7828>
- Luiz-Silva, W & Oscar-Júnior, A.C. 2022, 'Climate extremes related with rainfall in the State of Rio de Janeiro, Brazil: a review of climatological characteristics and recorded trends', *Natural Hazards*, vol. 114, pp. 713-732, <https://link.springer.com/content/pdf/10.1007/s11069-022-05409-5.pdf>
- Luiz-Silva, W.; Silva, F.P.; Dereczynski, C.P. & França, J.R.A. 2023, 'Towards a link between climate extremes and thermodynamics patterns in the city of Rio de Janeiro – Brazil: climatological aspects and identified changes', *Journal of Geoscience and Environment Protection*, vol. 11, pp. 131-160, DOI: 10.1007/s11069-022-05409-5
- Marengo, J.A. & Nobre, C.A. 2024. 'Secas e cheias mais que dobraram no Brasil entre 2014 e 2023', viewed 17 August 2024, <<https://amda.org.br/opiniao/secas-e-cheias-mais-que-dobram-no-brasil-entre-2014-e-2023/#:~:text=Forum%20406%20epis%C3%B3dios%20de%20secas.>>
- Martins, S.M.B.O. 2012, 'Caracterização Sinótica E Climatológica De Eventos De Chuva Pós-Frontal No Rio De Janeiro', Monografia do Departamento de Meteorologia da UFRJ, <https://pantheon.ufjf.br/handle/11422/20777>
- MJSP – Ministério da Justiça e Segurança Pública. 2023. viewed August 15, 2024, <<https://www.gov.br/mj/pt-br/assuntos/noticias/mj-sp-edita-portaria-que-estabelece-estrategias-de-protecao-a-saude-dos-consumidores-em-grandes-eventos-portaria-35.pdf>>.
- Monteiro dos Santos, D., Libonati, R., Garcia, B.N., Geirinhas, J.L., Salvi, B.B, Lima e Silva, E., Rodrigues, J.A., Peres, L.F., Russo, A., Gracie, R., Gurgel, H. & Trigo, R.M. 2024, 'Twenty-first-century demographic and social inequalities of heat-related deaths in Brazilian urban areas', *PLoS ONE*, vol. 19, no. 1, e0295766, DOI: 10.1371/journal.pone.0295766
- National Geographic. 2023. Viewed 19 July 2024, <<https://www.nationalgeographicbrasil.com/meio-ambiente/2023/11/ondas-de-calor-records-de-temperatura-e-el-nino-potentos-alertas-sobre-as-mudancas-no-clima.>>.
- Nehren, U., Kirchner, A., Sattler, D., Turetta, A.P. & Heinrich, J. 2013, 'Impact of natural climate change and historical land use on landscape development in the Atlantic Forest of Rio de Janeiro, Brazil', *Annals of the Brazilian Academy of Sciences*, vol. 85, no. 2, pp. 497-518, <https://www.scielo.br/j/aabc/a/xhyZP6TSqDBRzmFzzzCJkgv/?format=pdf>
- Neiva, H.S., Silva, M.S. & Cardoso, C. 2017, 'Analysis of climate behavior and land use in the city of Rio de Janeiro, RJ, Brazil', *Climate*, vol. 5, no. 3, pp. 52, <https://www.mdpi.com/2225-1154/5/3/52>
- NOAA. 2023a. 'Earth had its warmest November on record | National Oceanic and Atmospheric Administration (noaa.gov)', viewed 19 July 2024. <<https://www.noaa.gov/news/earth-had-its-warmest-november-on-record.>>.
- NOAA, 2023b. '2023 was the world's warmest year on record, by far | National Oceanic and Atmospheric Administration (noaa.gov)', viewed 19 July 2024, <<https://www.noaa.gov/news/2023-was-worlds-warmest-year-on-record-by-far.>>.
- Pimentel, L.C.; Marton, E.; Silva, M. S. & Jourdan, P. 2014, 'Caracterização do regime de vento em superfície na Região Metropolitana do Rio de Janeiro', *Eng. Sanit. Ambient.*, vol. 19, no. 2, pp. 121-132, DOI: 10.1590/S1413-41522014000200003
- Pinkerton, K.E. & Rom, W.N. 2021, 'Climate change and global public health', *Respiratory Medicine*, Springer Publisher, 605 pp.
- Prefeitura do Rio de Janeiro. 2024, viewed 15 August 2024, <https://doweb.rio.rj.gov.br/apifront/portal/edicoes/imprimir_materia/1070470/6662>.
- Pristo, M.V.J.; Dereczynski, C.P.; Souza, P.R. & Menezes, W.F. 2018, 'Heavy rainfall events climatology in the city of Rio de Janeiro', *Revista Brasileira de Meteorologia*, vol. 33, no. 4, pp. 615-630, <https://www.scielo.br/j/rbmet/a/RsP5CT4MLXwVdXXnkNtSBXL/?lang=pt>.
- Rivera, J.A., Arias, P.A., Sörensson, A.A. et al. 2023. '2022 early-summer heatwave in Southern South America: 60 times more likely due to climate change', *Climatic Change*, vol. 176, no. 102, DOI: 10.1007/s10584-023-03576-3
- Satyamurty, P., Nobre, C.A. & Silva Dias, P.L. 1998, 'Tropics – South America. In: Meteorology of the Southern Hemisphere. Eds. Karoly, D.J. & Vincent, D.G. *American Meteorological Society, Meteorological Monographs*, v. 27, n. 49, p. 119-139, https://link.springer.com/content/pdf/10.1007/978-1-935704-10-2_5.pdf

- Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C. et al. 2021, 'Weather and climate extreme events in a changing climate'. In *Climate Change, 2021: The physical science basis. contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change* [Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Pean C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekci O, Yu R, and Zhou B (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1513–1766. *Weather and Climate Extreme Events in a Changing Climate* (Chapter 11) – *Climate Change 2021 – The Physical Science Basis* (cambridge.org). <<https://www.cambridge.org/core/books/climate-change-2021-the-physical-science-basis/weather-and-climate-extreme-events-in-a-changing-climate/5BCB24C5699F1D42B2DE379BDD4E2119>>.
- Solórzano, A., Oliveira, R.R. & Lazos-Ruiz, A.E. 2016, 'Landscape Reading methodology of urban forests: interpreting past and current socioecological interactions in Rio de Janeiro', *HALAC*, vol. 6, no. 1, pp. 211-224, <https://pdfs.semanticscholar.org/e9b8/362f2760c09ad4f4f253ee54cb2569664437.pdf>
- Thom, E.C. 1959, 'The discomfort index', *Weatherwise*, vol.12, no.1, pp. 57-60, DOI: 10.1080/00431672.1959.9926960jun/19

Author contributions

Claudine Dereczynski: conceptualization; methodology; writing-original draft; supervision. **Wanderson Luiz-Silva:** methodology; writing – original draft; visualization. **Anna Carolina Bazzanela:** data curation; formal analysis; visualization. **Airton Bodstein:** writing – original draft. **Sin Chan Chou:** methodology; writing – review and editing; supervision.

Conflict of interest

The authors declare no conflict of interest.

Data availability statement

All data included in this study are publicly available in the literature.

Funding information

Not applicable.

Editor-in-chief

Dr. Claudine Dereczynski

Associate Editor

Dr. Herminio Ismael de Araújo-Júnior

How to cite:

Dereczynski, C., Luiz-Silva, W., Bazzanela, A.C., Bodstein, A. & Chou, S.C. 2024, 'Case Study of an Extreme Heat Wave in Rio de Janeiro on November 2023: Synoptic Conditions and Climatological Trends', *Anuário do Instituto de Geociências*, 47:66182. https://doi.org/10.11137/1982-3908_2024_47_66182