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Brazil Climate Highlights 2023

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Keywords:	extreme precipitation, intense winds, heatwaves, synoptic-scale cyclones, Brazil

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Abstract

In 2023-year the Earth experienced the highest near-surface temperature anomalies ever recorded until that moment. As consequence, several extreme weather and climate events occurred around the world, including the Brazil. In this sense, the main goal of this study is to describe the observed anomalous temperature and precipitation as well as the most significant extreme events occurred in Brazil in 2023-year. Different datasets and methodologies were applied. The north coast of the state of São Paulo had the highest accumulation of rainfall recorded in Brazil in a single day. September, October and November 2023 experienced large precipitation deficits over the Amazon region leading to a very intense-prolonged drought period. The south of Brazil was affected by a large amount of precipitation in a short time associated with cyclones, resulting in fatalities and economic losses. Southeast and Central-West Brazil experienced two intense heatwaves in the austral spring, breaking daily temperature records in major cities like São Paulo and Rio de Janeiro. These heatwaves were driven by an anomalous persistent mid-tropospheric ridge over central and Southeastern Brazil. Overall, the main physical processes responsible for these extremes are described as well as the socio-environmental impacts caused by most of them.

Keywords: extreme precipitation, intense winds, heatwaves, synoptic-scale cyclones, Brazil

1. Introduction

As per the Intergovernmental Panel on Climate Change (IPCC, 2023), the global average temperature has risen by 1.1ºC between 2011-2020 compared to the 1850-1900 period. This rise is notably more intense over landmasses than over oceans, with various regions around the world experiencing distinct temperature shifts. From the 1970s onward, the global average temperature has escalated at a swifter rate than during any other 50-year span within the last 2000 years (IPCC, 2023).

According to the World Meteorological Organization (WMO, 2024), in 2023-year the globe experienced its higher global temperature anomaly ever recorded in the entire history of measurements: 1.48ºC warmer than pre-industrial levels (1850-1900) and 0.6ºC warmer than the 1991-2020 climatology, surpassing previous records set in 2016 (+1.29ºC) and 2020 (+1.27ºC). The months from June to December 2023 marked the hottest period on record. September 2023 stood out with the highest global average temperature anomaly (+0.93ºC compared to the 1991-2020 climatology), followed by October, November, and December, each setting the second-highest records (with anomalies of +0.85ºC in each month) (Copernicus, 2024).

Every day of the 2023-year recorded a global average anomaly of 1ºC above pre-industrial levels, with over half of these days experiencing anomalies above 1.5ºC and two days (November 17 and 18) surpassing 2ºC being the first time this has occurred (Copernicus, 2024). These records are alarming, considering that The Paris Agreement (2016) aims to limit the increase in global average temperature to a maximum of 1.5ºC - 2ºC.

It is unequivocal that human actions associated with greenhouse gas emissions (GHGs) have contributed to global warming (IPCC, 2021). In 2023, atmospheric concentrations of carbon dioxide and methane continued to rise and reached record levels (419 ppm and 1.902 ppb, respectively) (Copernicus, 2024).

In addition to the record in near-surface air temperatures in 2023, the oceans also recorded elevated Sea Surface Temperatures (SSTs). Global SSTs were elevated in March, declined in April and May, and increased again from June, reaching 21.02°C on August 23 and 24, 2023, which was higher than the previous record of 20.95°C observed in March 2016 at the end of a strong El Niño event. For the rest of the year, global average SSTs remained exceptionally high, surpassing previous records for warmest years. The Pacific Ocean was characterized by a rapid transition from La Niña to El Niño. The La Niña lasted for 3 years, and by July 2023, the warm phase of the phenomenon was already established (Copernicus, 2024).

A large number of extreme events were recorded worldwide in 2023 affecting human health, ecosystems, nature, and infrastructure, such as heatwaves over China, North America and Europe (Cheng Qian et al., 2024; Zachariah et al., 2023), Brazil (Kew et al., 2023); floods over Africa (Kimutai et al., 2023); droughts in Amazon River Basin (Clarke et al., 2024) and West Asia (Otto et al., 2023); and wildfires in Canada (Wang et al., 2024).

According to the National Institute of Meteorology (INMET, 2024), over the Brazil, the temperature was 0.69ºC above the 1991-2020 climatology of 24.23ºC, making it the hottest year. This record surpassed the highest values of anomalies ever recorded in the country: in 2015 (+0.67ºC), 2019 (+0.61ºC), 2016 (+0.43ºC) and 1998 (+0.37ºC). In nine months of 2023-year, the average temperature anomaly was above the historical average, with September 2023 recording the highest anomaly (+1.6ºC), following the global pattern.

The Climate Study Group (GrEC) from University of São Paulo (USP) - Brazil also conducts climate monitoring and forecasting for Brazil and monthly highlights the occurrence of extreme events (Bueno et al., 2023) that can be accessed at http://www.grec.iag.usp.br/.

Records of temperature and precipitation were registered in Brazil in 2023. Araçuaí (MG) recorded on November 19th, 2023 the highest temperature ever recorded in the country of 44.8°C (INMET) of 44.8°C. The previous highest value was in Teresina (PI), on 11/21/2005, reaching a maximum of 44.7°C. Bertioga (SP) recorded the highest precipitation accumulations ever registered in the country by INMET and CEMADEN (National Center for Monitoring and Alerting of Natural Disasters): 683 mm in a 24-hour period between February 18 and 19, 2023 (Marengo et al., 2024). The previous record occurred in 2022 in Petrópolis (RJ) of 534.4 (CEMADEN; Bartolomei et al., 2023), and in 1991 in Florianópolis (SC) of 404.8 mm (INMET). Another highest rainfall accumulations in 24-hours was of 346,6 mm occurred in January 5, March 10 and December 12 and 31, 1999 observed over the mean domain on central-north coast of the São Paulo state that includes the Bertioga (da Silva et al., 2021).

Associated with extreme precipitation and temperature in Brazil, the occurrence of natural disasters has been increasing in the country. According to the CEMADEN, the country recorded 1.341 disaster events in 2023, with 815 of hydrological origin and 526 of geological origin. The number of events is the highest ever recorded since the beginning of CEMADENS's operation in 2011. The region with the highest number of occurrences was the Southeast of Brazil. It is estimated that the economic losses associated with these events were nearly R$ 25 billion, with 74.000 people left homeless, 500.000 displaced, 9.263 people injured, and 132 lives lost (CEMADEN, 2024).

The aim of this study is to describe (a) the behaviour of temperature and precipitation and (b) the most significant extreme events occurred in Brazil in 2023-year (as highlighted in the GrEC's climate meetings in 2023) through collaborative work by various researchers and students from GrEC. We explore (1) the wet event at the coast of São Paulo state; (2) the drought in the Amazon Region; (3) the extreme precipitation in South of Brazil; and (4) the record-breaking heat waves of spring.

2. Methodology

2.1 Study Area and Data

Brazil is the study area and the data used in this work are provided by different sources as summarized in **Table 1**. We used observed data from INMET meteorological stations; pluviometers from the Environmental Observation Network of the CEMADEN, of the Ministry of Science, Technology and Innovation (MCTI); European Centre for Medium-Range Weather Forecasts (ECMWF) v5 reanalysis (ERA5). ERA5 is the fifth generation ECMWF atmospheric reanalysis produced by the Copernicus Climate Change Service (C3S), in a global grid of 0.25° x 0.25° (Hersbach et al. 2019). We also used precipitation and 10-m winds from Multi-Sensor Weather (MSWX), which has a high spatial and temporal resolution (0.1° and 3-hourly, respectively) bias-corrected near surface atmospheric variables with global coverage (Beck et al. 2022). A summary of the analyses conducted can be seen in the flowchart in **Figure 1**. Sections 2.3 to 2.6 describe in detail the methodologies employed.

SOURCE	VARIABLES	PERIOD	TEMPORAL RESOLUTION	SPATIAL RESOLUTION	REFERENCE
ERA5	SST, vertical velocity, air temperature at 2 m, geopotential height at 500 hPa, zonal wind speed at 200 hPa and specific humidity at 850 hPa, mean sea level pressure,1000 to 500 hPa geopotential, 200-hPa and 850-hPa zonal and meridional wind, 850-hPa streamlines, 500-hPa air temperature, 500-hPa cyclonic relative vorticity, and 500-hPa omega.	1991-2023	daily and monthly	0.25º X 0.25º	Hersbach et al. (2020)
INMET meteorological stations	precipitation, maximum temperature, compensated average temperature	1961-2023	daily	625 conventional stations	https://bdmep.inmet.gov.br/
CEMADEN rain gauges	precipitation	2013-2023	10 min (with rain) 1 hour (no rain)	65 rain gauges located on the coast of São Paulo	https://mapainterativo.cemaden.gov.br/
MSWX (Multi-Source Weather)	temperature, precipitation and wind velocity	1991-2023	3-hourly	0.1° X 0.1°	Beck et al. (2022)
GOES-16	temperature at the top of convective clouds (infrared channel images CH13, 10.35 μm captured by the Advanced Baseline Imager (ABI) sensor	Feb 19th at 00 UTC	10min	2Km	
NOAA	SST	February, 2023	daily	0.05° x 0.05°	Liu et al. (2017)

Table 1: Data used in this study.

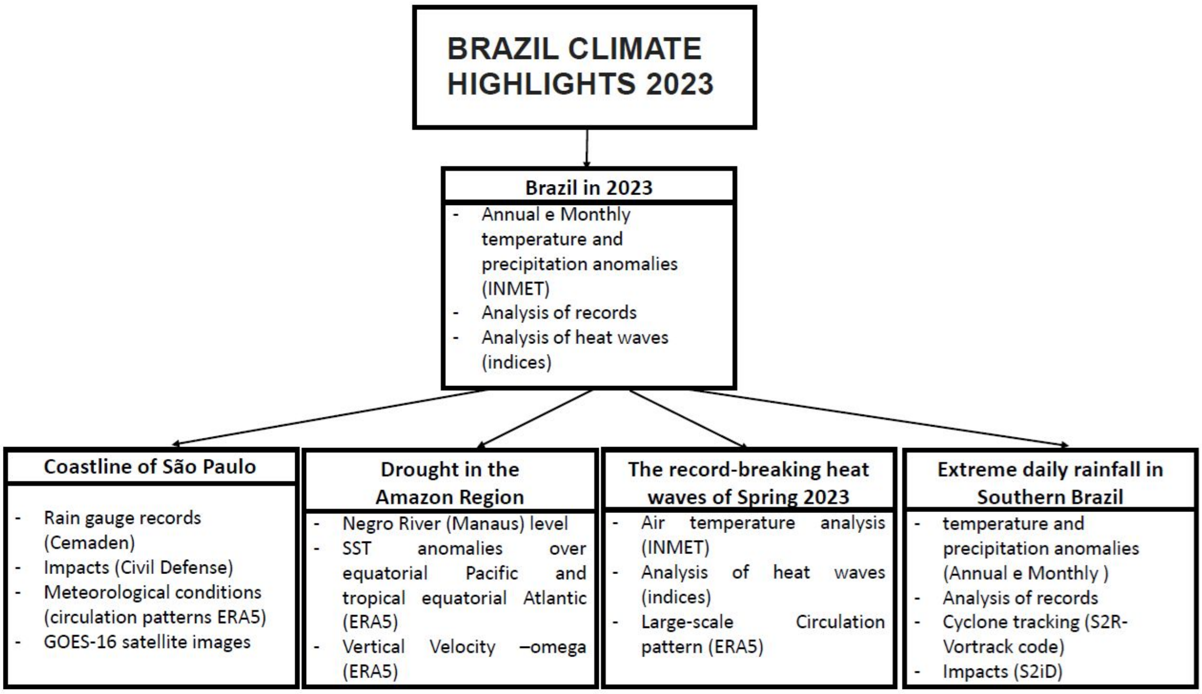


Figure 1: Flowchart summarizing the methodology applied in this study.

2.2 Station Data and Extreme Events

The temperature and precipitation anomalies in Brazil during 2023-year were investigated using data observed at conventional meteorological stations from INMET. The variables of compensated average temperature, maximum temperature and daily precipitation were collected from 625 stations, covering the period from 1961 to 2023. Data quality control for missing data was applied only for the period from 1991 to 2023. Series with more than 10% missing data were excluded. We did not assess earlier years because historical information is scarcer, and we wanted to retain as many stations as possible in the study. The quality control selected 69 stations for compensated average temperature, 93 for maximum temperature, and 118 for precipitation **(Figure 2)**.

(a) (b) (c)

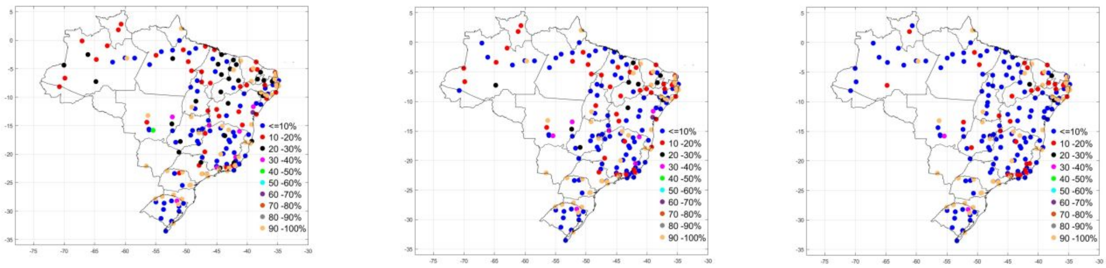


Figure 2: Percentage of missing daily data for conventional stations from INMET (1991-2023) for: (a) compensated average temperature (^{o}C) (b) maximum temperature (^{o}C) and (c) precipitation (mm).

Annual and monthly anomalies for compensated average temperature and precipitation for each station were calculated for 2023. The occurrence of compensated average temperature and maximum temperature records in 2023 was investigated for the available period of each station, since 1961.

Precipitation and temperature indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI, Karl et al., 1999 and Peterson et al., 2001) were used to investigate the occurrence of extreme events. For temperature, the Warm Spell Duration Index (WSDI) was calculated to identify the occurrence of heatwaves in 2023. WSDI is calculated first defining the daily maximum temperature on day i in period j (TXij) and the 90th percentile for the calendar day centered on a 5-day window (TXin90), based on the climatology of the 1991-2020. The number of days where TXij>TXin90 for at least 6 consecutive days is the WSDI. Additional indices were computed to provide other aspects of the heat wave events, based on the WSDI definition of a heat wave, including: the yearly number of heat waves events (HWN); the length of the longest heat wave event of the year (HWD); and the average magnitude of heat wave (HWM), which is obtained by averaging the maximum temperatures of all heat wave days during 2023-year.

2.3. Coast of the São Paulo state

For the coast of São Paulo, the precipitation data observed by 65 pluviometers from CEMADEN were used. This dataset is available from 2013 to the present. To analyse the atmospheric conditions, we used hourly variables from the ERA5: mean sea level pressure, 1000-500-hPa geopotential, 200-hPa and 850-hPa zonal and meridional wind, 500-hPa air temperature, relative vorticity and omega.

The top of convective clouds, for 06 UTC on February 18 and 19, were identified in the infrared channel images (CH13, 10.35 μm) captured by the Advanced Baseline Imager (ABI) sensor on board the Geostationary Operational Environmental Satellite - 16 (GOES-16). The ABI sensor data set is available at 10-minute intervals, with a spatial resolution of 2 km and is processed by the Center for Weather Forecasting and Climate Studies (CPTEC) of the National Institute for Space Research (INPE). The daily SST was obtained from the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (CRW), with horizontal resolution of 0.05° (Liu et al., 2017).

2.4 Drought in the Amazon Region

The Amazon drought event was investigated by producing 2023 anomalies of SST and circulation cross sections (from 1000 to 100 hPa) using ERA5. The anomalous vertical velocity (omega) meridionally averaged (between 10ºN and 10ºS) for the western Pacific-northern South American region (between 10ºN and 10ºS and 150ºE and 40ºW) and for the Atlantic-northern South American region (between 40ºN and 25ºS and 70ºW and 40ºW) for September, October, and November 2023, with anomalies computed with respect to the 1991 to 2020.

2.5 South of Brazil

In this work, cyclones are tracked by applying the S2R-Vortrack code developed by Sugahara (2000) and Reboita et al. (2010). The cyclone's identification is based on the relative vorticity of the wind at 10 m (negative values in the Southern Hemisphere), which involves three stages. First, it is the identification of minimum relative vorticity, which must be less than or equal to -1.0×10^{-5} s^{-1}applying nearest neighbour approach. When the first position is found, the algorithm corrects applying a high resolution grid in a 250 km radius. After, as a second stage, the first position is used in the second time-step as a reference. It is calculated as the difference between two positions, known as the velocity of displacement of the system. Finally, this velocity is used as the first guess to obtain the new subsequent position, and searching for the minimum relative vorticity surrounding this location. This procedure continues until the maximum of 10 days and a minimum cyclone lifecycle is set as 1 day.

The cyclones were tracked using the wind field at 10 m height provided by ERA5 reanalysis to obtain the 1991–2020 climatology and 2023 cyclogenesis, which refers to the first time when a cyclone is identified. Cyclogenesis density, on the other hand, is defined as the number of cyclogenesis events occurring within a 3º x 3º latitude by longitude grid. This density is calculated as the total number of events divided by the grid area in square kilometers, multiplied by 10^5, and then divided by the number of years to determine the annual average (Crespo et al., 2020; de Jesus et al., 2021). We discuss the cyclogenesis annual mean for 2023 as well as the anomaly, represented by the difference between 2023 and the 1991–2020 climatology.

In addition, we selected the four most intense cyclones of 2023 to analyse the associated accumulated precipitation and its relative contribution for monthly climatology of precipitation, maximum wind speed along lifecycle, and the difference between the daily precipitation on cyclone days and the 95th percentile (P_{95}). These cyclones occurred in: July 14h to 22, July 12 and 16, September 2 to 5 and October 3 and 6.

The accumulated precipitation over the lifecycle of each cyclone was calculated by summing the daily precipitation values. The relative contribution to the monthly precipitation climatology was determined as the ratio between this accumulated precipitation and the monthly average precipitation based on the 1991–2020 climatology, expressed as a percentage.

The maximum wind speed throughout the lifecycle was identified by determining the highest wind speed recorded each day of the cyclone's life. We analysed the wind field on the day with the highest wind speed.

The P_{95} value was derived from daily precipitation data from 1991–2020 over the southern Brazil domain (35°S–22.1°S, 59°W–46.1°W). We then calculated the difference between the daily accumulated precipitation during cyclone days and the P_{95} threshold, reporting the largest observed difference.

The impacts of the cyclones were obtained by utilizing the damage management report from the Integrated System of Information on Disasters (S2ID - http://S2iD.mi.gov.br) of the Brazilian Civil Defense, administered by the Ministry of Integration and Regional Development of Brazil, with a specific focus on extreme climatic events occurring in the southern region of the country.

2.6. The record-breaking heatwaves of Spring 2023

Variables from ERA5 reanalysis are used to investigate the large-scale circulations associated with heatwave episodes. Air temperature at 2 m (t2m) is used to verify whether the ERA5 reanalysis reproduces the spatial patterns and magnitude associated with heat waves. Geopotential height at 500 hPa, zonal wind speed at 200 hPa and specific humidity are used to characterize circulation anomalies associated with heat waves. Daily data for atmospheric variables are used to calculate the anomalies based on the seasonal (September-October-November) 1991 to 2020 climatology. These anomalies considered the two prolonged heatwave events observed in September 17–27 and November 11–18, 2023. The choice of the periods is based on the analysis of heat wave events identified at the Mirante de Santana meteorological station in São Paulo, Brazil (not shown), considering periods with maximum temperatures above the 90th percentile for a calendar day centered on a 5 day window for at least six consecutive days. Additionally, were calculated the daily average anomalies of maximum surface air temperatures for the Central-West and Southeast Brazil during 2023-year austral spring (September 1 to November 30). The anomalies were computed using data from 36 INMET meteorological stations inside these regions.

3. Results

3.1. Brazil in 2023

The annual anomaly of compensated average temperature in 2023 was positive for almost all the stations used (92.75%), with the anomaly recorded as the highest in 25 of them since 1961 (stations marked with *), indicating a warming pattern in Brazil in 2023 **(Figure 3a)**. Comparing the average of the annual anomalies for all 69 stations, 2023 stands out as the hottest year (+0.84°C), followed by 2019 (+0.76°C), and 2015 (+0.74°C). The annual precipitation anomaly was positive in the south and at some stations in the Southeast and Northeast of Brazil. In the other parts of the country, negative anomalies were recorded **(Figure 3b)**. In 2023, three stations in Rio Grande do Sul state (Southern Brazil) experienced the highest precipitation anomalies (marked with Δ), while 10 stations in the North, Northeast, and Southeast of Brazil recorded the lowest precipitation anomalies (marked with ∇).

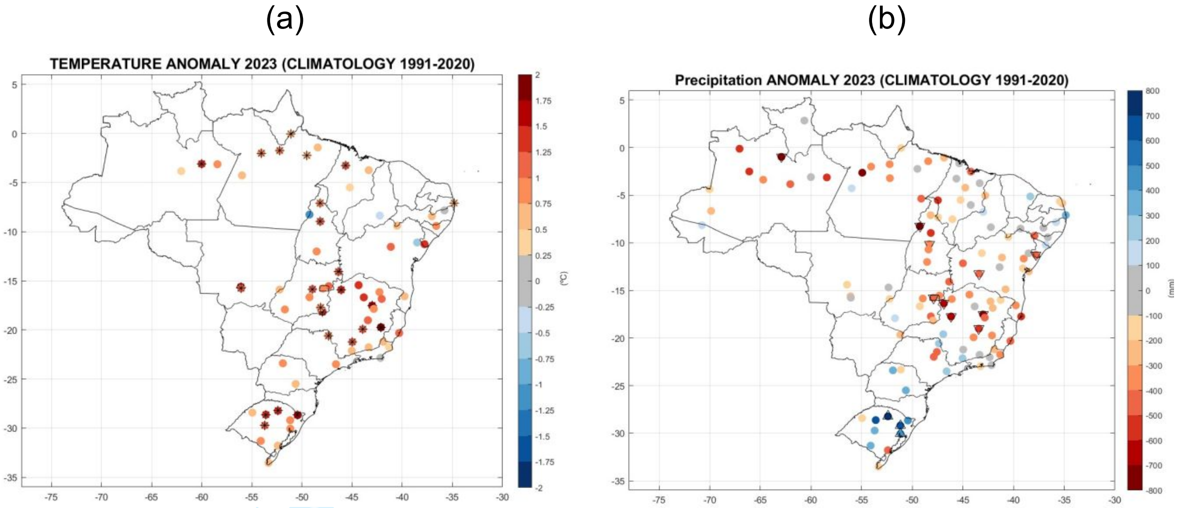


Figure 3: Annual anomalies for 2023 for INMET conventional meteorological stations using 1991-2020 climatology: **(a)** Compensated average temperature (ºC) (the stations where the highest temperature anomaly was recorded in 2023 are marked with *); **(b)** Precipitation (mm) (stations where the highest precipitation anomaly was recorded in 2023 are marked with Δ, while the lowest precipitation anomaly was recorded in 2023 are marked with ∇).

For the monthly anomalies of compensated average temperature, it is possible to observe that in January **(Figure 4a)**, only Rio Grande do Sul state registered warmer conditions, while the rest of the country had temperatures within or below average. In February and March **(Figure 4b,c)**, the warmer temperatures extended to the southeast and central-west regions of the country. In April **(Figure 4d)**, Rio Grande do Sul state had below-average temperatures, while parts of the northeast, north, and southeast showed positive anomalies. In May and June **(Figure 4e,f)**, positive anomalies intensified in southern Brazil, with monthly records in both the south and north (marked with *). From July onwards **(Figure 4g-l)**, the country experienced higher positive temperature anomalies, with several monthly records (marked with *) and the largest monthly anomalies observed in 2023 (except for October, which had negative anomalies in Rio Grande do Sul).

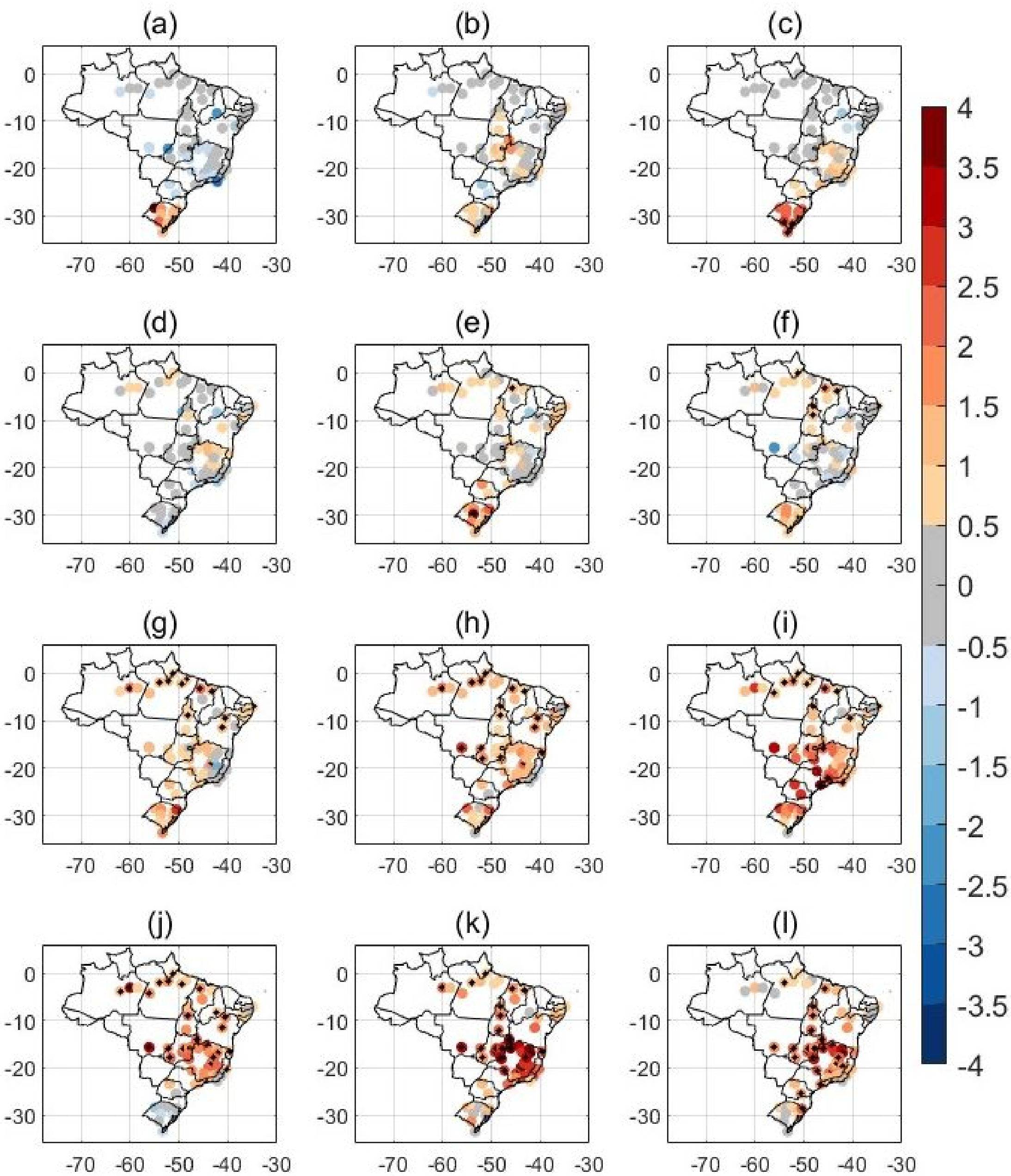


Figure 4: Compensated average temperature (ºC) monthly anomalies for 2023 for INMET conventional meteorological stations using 1991-2020 climatology: for **(a)** January, **(b)** February, **(c)** March, **(d)** April, **(e)** May, **(f)** June, **(g)** July, **(h)** August, **(i)** September, **(j)** October, **(k)** November, and; **(l)** December (in ºC) (the stations with the highest temperature monthly anomaly are marked with *).

Figure 5 presents the stations with the highest temperatures in the series. In 2023, 17 (24.64%) out of 69 stations set a record for compensated average temperature **(Figure 5a)**, and 23 (24.73%) out of 93 recorded a record for maximum temperature **(Figure 5b)**. The records of maximum temperature occurred 4 times in September, 7 in October, 11 in November and 1 in December. The highest maximum temperature of 44.8ºC ever recorded in Brazil was observed in Araçuaí (MG) on November 19 **(Figure 5b).**

(a) (b)

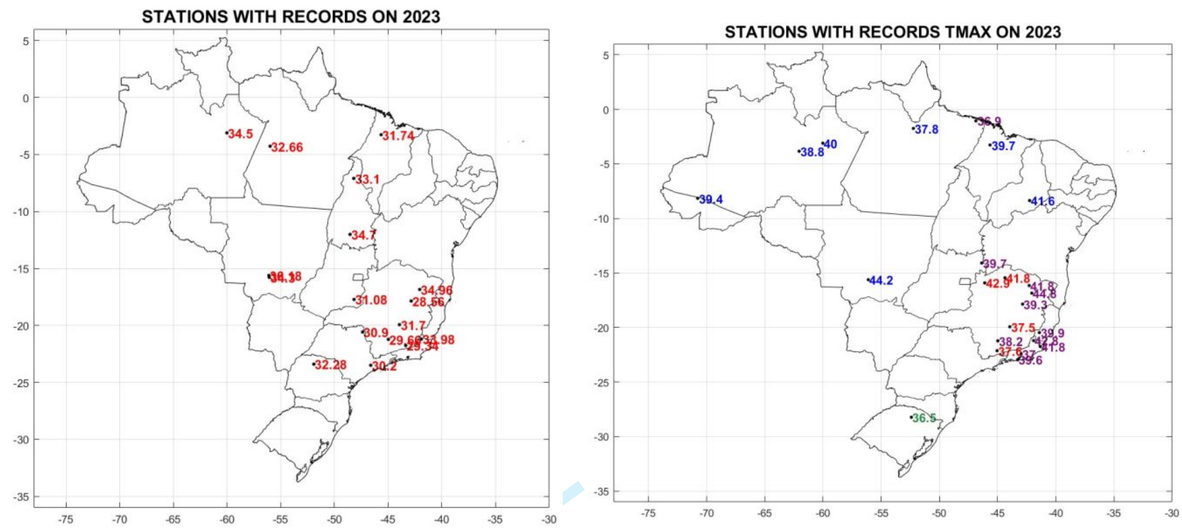


Figure 5: INMET conventional meteorological stations with records considering 1961-2023 period : **(a)** Compensated average temperature (ºC); **(b)** Maximum temperature (ºC). The occurrences in September are in red (4 times), October are in blue (7 times), November are in purple (11 times) and December are in green (1 time).

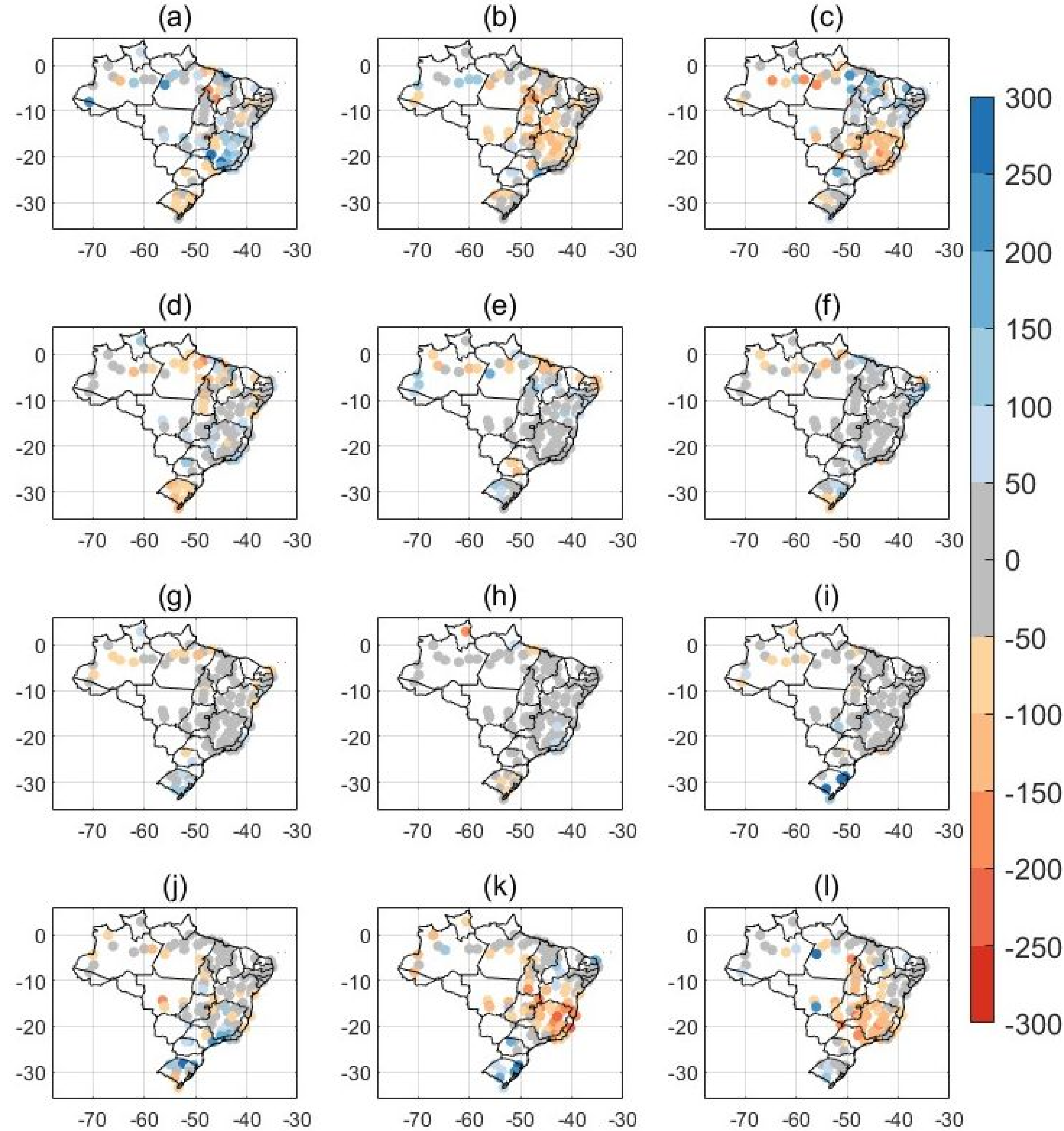


Figure 6: Precipitation monthly anomalies for 2023 for INMET conventional meteorological stations using 1991-2020 climatology: **(a)** January, **(b)** February, **(c)** March, **(d)** April, **(e)** May, **(f)** June, **(g)** July, **(h)** August, **(i)** September, **(j)** October, **(k)** November, and **(l)** December (in mm).

Regarding heatwave events, the highest values of WSDI were recorded at INMET stations located in the central-northern region of Brazil. In 2023, one station in the state of Pará and another in the state of Paraíba recorded 8 and 20 heat wave events, respectively, which together totalized more than 100 days (WSDI) at each station (**Figure 7a**). The highest occurrences of heatwaves during the year (HWN) were observed in stations in the states of Pará, Maranhão and Paraíba (**Figure 7b**). The station in Paraíba recorded the highest number of occurrences, with 20 heatwave events, and also registered the highest WSDI totalizing 160 heat wave days. Most of the stations located in the states of Bahia, Tocantins, Goiás and Minas Gerais recorded between 2 and 8 heatwaves events throughout the year. The most prolonged heat waves (HWD) also occurred at stations in the central-northern region of Brazil (**Figure 7c**). Some stations in the North and Northeast regions recorded events lasting over 20 days, with two stations in the state of Pará recording heatwave episodes lasting 23 days. The two most intense heat waves recorded a magnitude of maximum average temperature of 40°C (**Figure 7d**), one in the state of Piauí and other in the state of Minas Gerais. This latter being associated with the highest maximum temperature ever recorded in Brazil (**Figure 4b**), which is also analysed in Section 3.5.

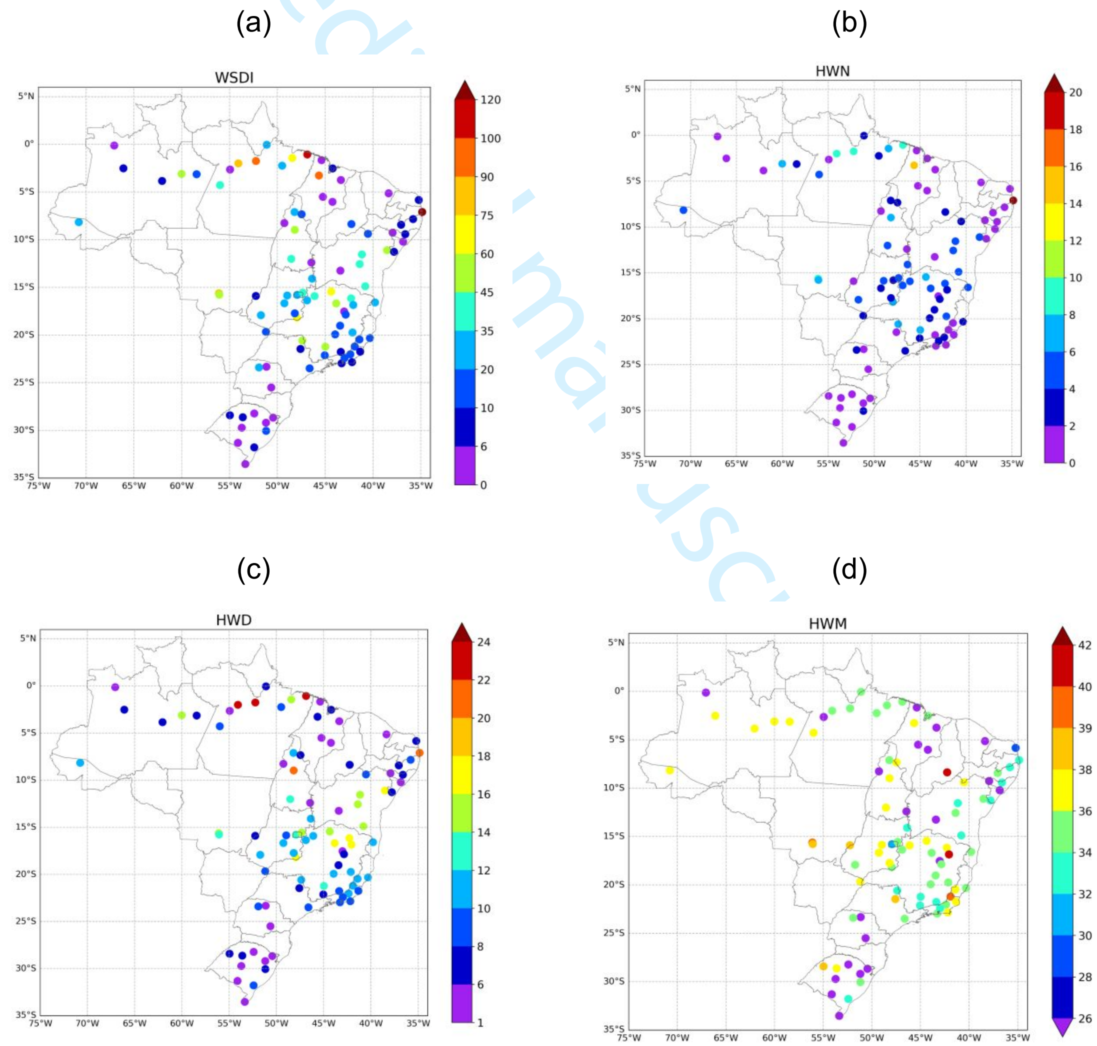


Figure 7: (a) WSDI index (in days); **(b)** yearly number of heat waves (HWN); **(c)** length (in days) of the longest heat wave of the year (HWD); **(d)** average daily magnitude (in °C) of all heat waves events (HWM) during 2023.

3.2. Coastline of São Paulo

From 15 UTC February 18 to 15 UTC February 19, 2023, on the north coast of the state of São Paulo, occurred the highest accumulation of rainfall recorded in Brazil in a single day (Marengo et al., 2024): 682.8 mm in just 24 hours in the municipality of Bertioga. Other significant accumulations were observed in São Sebastião (627.5 mm), Guarujá (474.8 mm), Ilhabela (337.3 mm), Ubatuba (334.9 mm) and Caraguatatuba (234.3 mm) (**Figure 8**). This event caused flooding, coastal erosion and landslides, resulting in human, environmental and economic impacts. According to the Civil Defense of the State of São Paulo, 1126 people lost their houses, 1090 people were displaced from their homes and 65 deaths were registered, as well as several blocked roads, collapsed barriers and falling trees. Although the highest accumulations of rainfall occurred in Bertioga, the highest number of deaths (64) was observed in São Sebastião due to the greatest occupation in precarious settlements and in risk areas, subject to mass movements on the slopes of the mountains of the Serra do Mar (Pedrassoli et al., 2023).

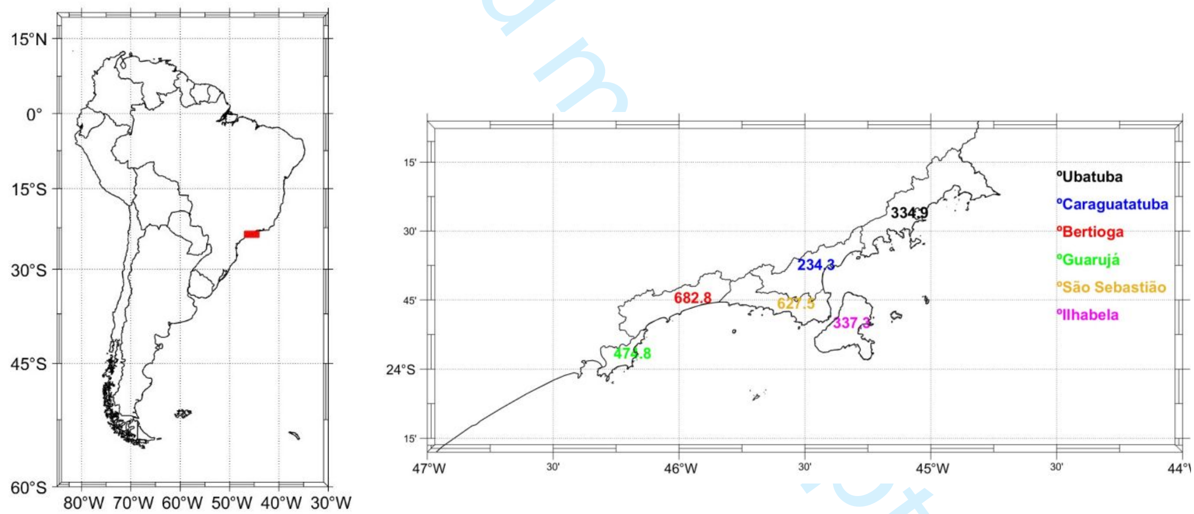


Figure 8: Precipitation accumulated in 24 hours (mm), from 15 UTC February 18 to 15 UTC February 19, 2023 on the Coast of São Paulo (red box on the left and highlighted on the left).

During this heavy rainfall event, the meteorological condition was marked by the passage of a polar cold front over the warmer than normal subtropical South Atlantic. On February 17-18, this cold front remained stationary over the state of Rio Grande do Sul, with the associated extratropical cyclone over the Atlantic Ocean, centered at approximately 52°W-46°S and with a central pressure of 974 hPa (**Figure**

9a). At upper levels, the jet stream (**Figure 9a**), the presence of a cyclonic circulation over the coast of the Northeast Region of Brazil and an anticyclonic circulation over the Central-West Region (**Figures not shown**) contributed to the pattern and movement of the frontal system. This pattern, which resembles typically a summer circulation over Brazil, was completed by the low level at 850 hPa flow from the Amazon towards the coast of São Paulo, which characteristics similar to the South American low-level jet, present between February 14-17 (**Figures not shown**). This low-level circulation contributed to increasing the availability of water vapor in the region, providing fuel to the heavy rainfall event. The anticyclonic circulation at upper levels progressively shifted westwards on February 18 12 UTC, while the cyclonic circulation moved towards the continent, where it remained until the end of February 19 (**Figures not shown**). Accompanying the pattern at upper levels, from February 18 onwards, the circulation at 850 hPa became disconfigured (**Figures not shown**).

On February 19, the frontal system moved eastwards and the extratropical cyclone intensified (**Figures 9b,d**). In addition, a mesocyclone formed in the lower troposphere, over the coast of the state of São Paulo, associated with intense 500-hPa cyclonic vorticity, which strengthened the upward movements (**Figure 9d**). The presence of the frontal system favored more intense winds from the adjacent South Atlantic towards the coast of São Paulo (**Figures not shown**). This circulation, combined with the orographic effect of the Serra do Mar, intensified the upward movements (**Figure 9d**) and contributed to the formation of deep convective clouds (**Figure 9f**). The South Atlantic, adjacent to the coast of São Paulo, was 1-2°C warmer than average (**Figures not shown**). This resulted in increased heat and moisture flux rates from sea to the atmosphere, strengthened by the intense winds associated with the cold front (Marengo et al., 2024). The combination of the synoptic cold front with local features (mountains of the Serra do Mar and intense near surface heat fluxes) resulted in intense and persistent precipitation over the north coast of the state of São Paulo.

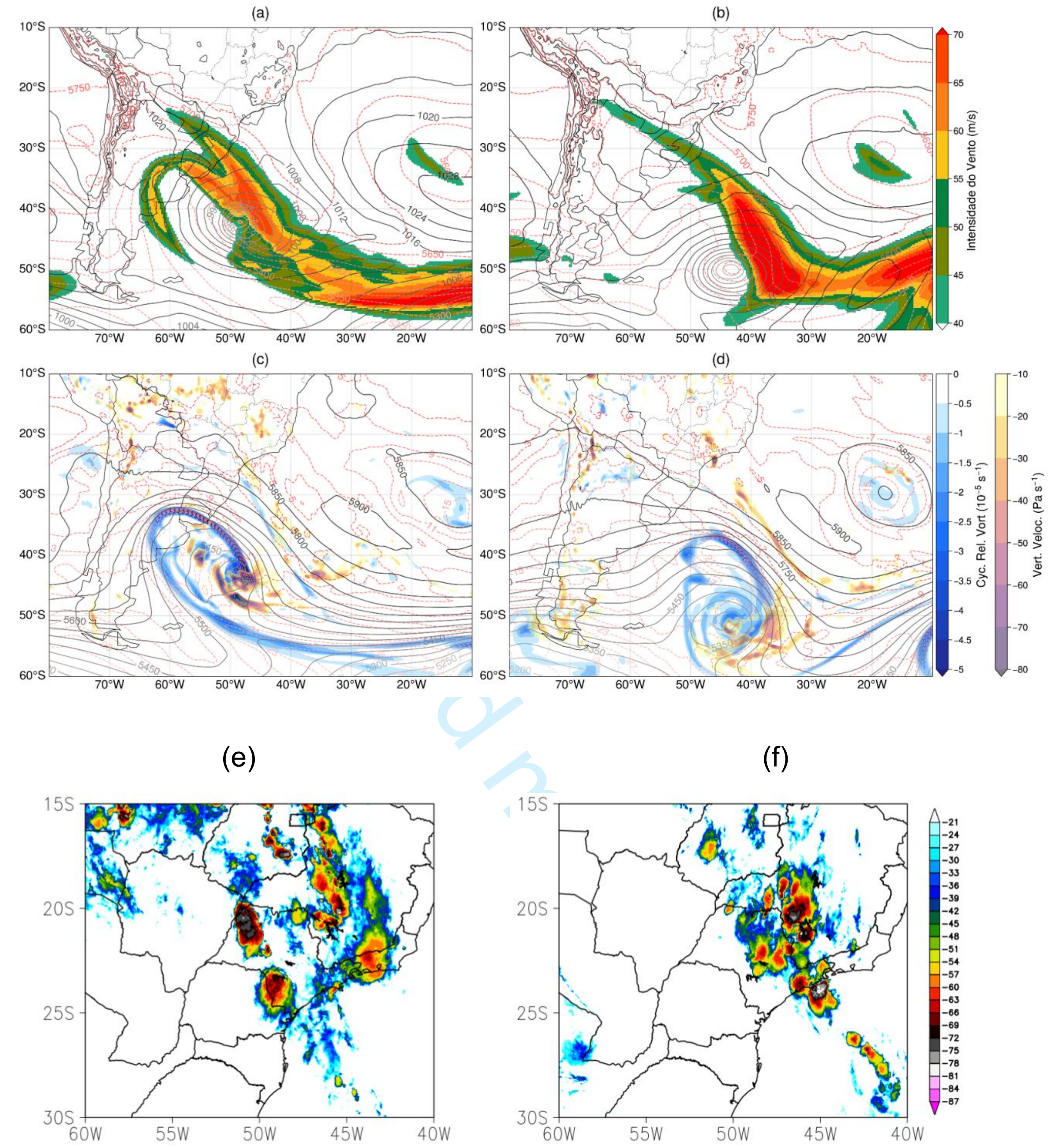


Figure 9: (a, b) Thickness between 1000-500 hPa layer (gpm, red lines), mean sea level pressure (hPa, black lines), and isotachs (m/s, shaded) at 250 hPa; **(c, d)** air temperature (°C, red lines), geopotential height (m, black lines), cyclonic relative vorticity (10^{-5} s^{-1}) and omega (hPa s^{-1}) at 500 hPa; (**e, f)** infrared images (CH13, 10. 35 μm) from the GOES-16 satellite for 06 UTC on February 18 (left column) and 19 (right column).

3.3. Drought in the Amazon region

Droughts in the Amazon region have been reported to occur during the combined manifestation of the El Niño phenomenon in the equatorial Pacific Ocean and abnormally warm conditions in the tropical north Atlantic Ocean (e.g., Marengo et al. 2008, Coelho et al. 2012). During the spring of 2023, a major drought event was observed in the Amazon region, with the Negro River in Manaus recording in November its lowest level of 12.7 m in 121 years. As shown in **Figure 6**, September, October and November 2023 experienced large precipitation deficits over the Amazon region, which contributed to such a low Negro River level in Manaus. **Figure 10** (left column panels) shows that from September to November 2023 the prevailing large scale forcing associated with the observed precipitation deficit in the Amazon were the a) El Niño phenomenon, with sea surface temperature anomalies larger than 2^{o}C in parts of the equatorial Pacific Ocean and b) anomalous sea surface temperature warming in the tropical equatorial Atlantic Ocean, with anomalies larger than 1^{o}C in parts of the equatorial Atlantic basin.

Figure 10 (central and right columns) shows vertical cross sections of anomalous vertical velocity (omega) meridionally averaged between 10^{o}N and 10^{o}S (central column panels), and vertical cross sections of anomalous vertical velocity (omega) zonally averaged between 70^{o}W and 40^{o}W (right column panels) for September, October, and November 2023. **Figure 10** (central column panels) shows that prevailing subsidence was noticed over the Amazon, as illustrated by positive vertical velocity (omega) anomalies east of 70^{o}W, and prevailing ascending vertical motion was noticed over the warmer than normal equatorial Pacific, as illustrated by negative vertical velocity (omega) anomalies east of 100^{o}W, depicting an anomalous Walker circulation in consistency with the observed El Niño conditions. **Figure 10** (right column panels) shows that prevailing subsidence was noticed over the Amazon, as illustrated by positive vertical velocity (omega) anomalies to the south of the equator. Also, prevailing ascending vertical motion was noticed over the north Atlantic, as illustrated by negative vertical velocity (omega) to the north of the equator, depicting an anomalous Hadley circulation in consistency with the observed anomalous sea surface temperature warming in the tropical north Atlantic Ocean.

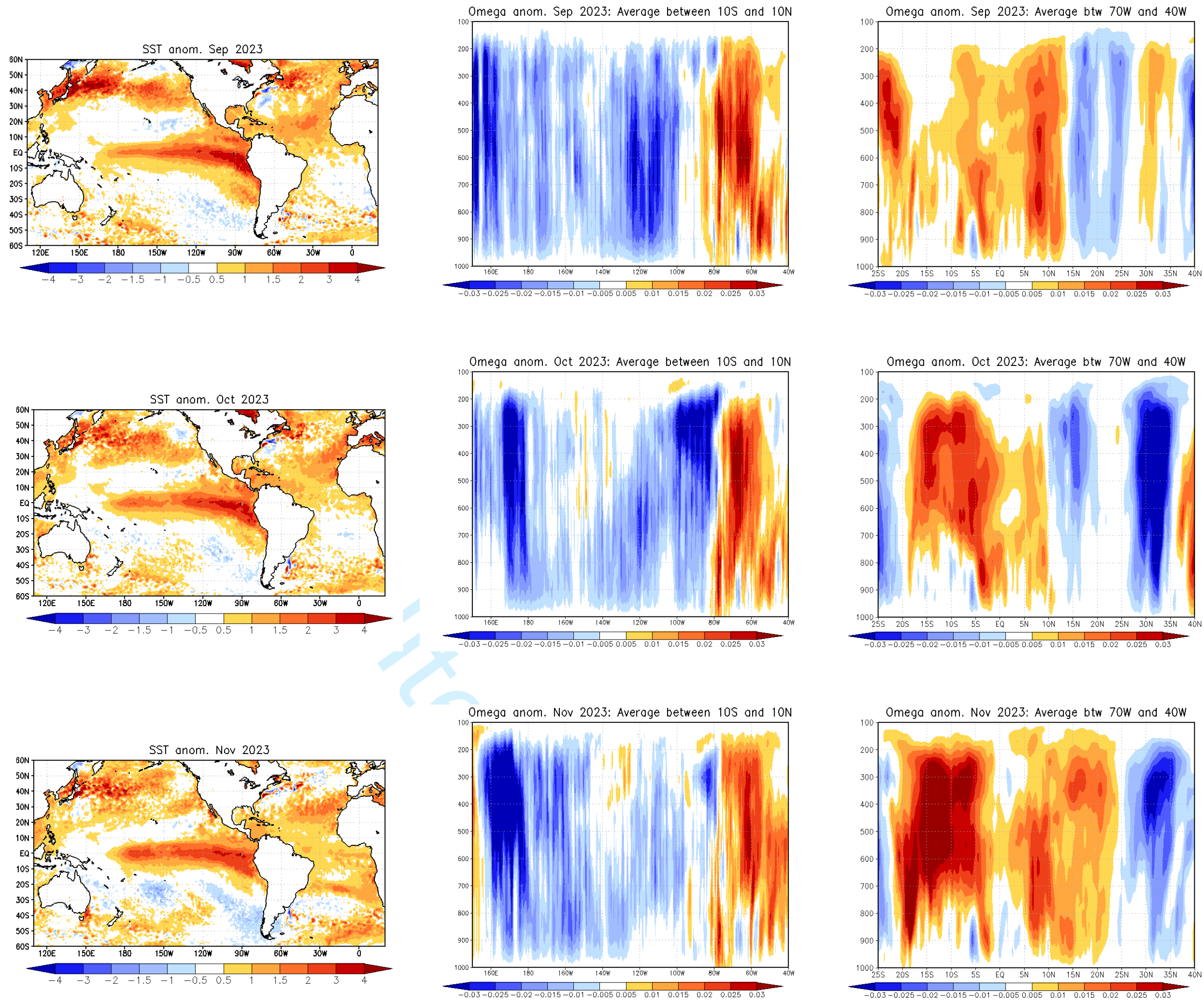


Figure 10: Sea surface temperature anomalies (left column panels), vertical cross sections of anomalous vertical velocity (omega, Pa.s^{-1}) meridionally averaged between 10ºN and 10ºS (central column panels), and vertical cross sections of anomalous vertical velocity (omega) zonally averaged between 70ºW and 40ºW (right column panels) for September, October, and November 2023. Anomalies anomalies were computed with respect to the 1991 to 2020 using ERA5.

3.4 Extreme daily rainfall in Southern Brazil

The 2023-year was characterized by high precipitation amounts, especially in the states of Rio Grande do Sul (RS) and Santa Catarina (SC) (**Figure 6**). Some episodes of daily extreme precipitation were associated with cyclones, and a total of four events (occurred in June, July, September and October) were selected based on their observed precipitation characteristics and impacts. For the four selected cyclones of 2023, **Figure 11** depicts the accumulated precipitation throughout the life cycle, the ratio between this precipitation and the monthly average precipitation, and the wind speed for the day with maximum winds during the cyclone's lifecycle. The cyclone from June 14 to 22, 2023 showed a very localized center of intense precipitation (~ 240 mm) over the eastern RS (**Figure 11a**). These 8 days were responsible for most of the monthly precipitation, with above 80% of the monthly climatological mean in the eastern part of RS (**Figure 11b**). The day with the maximum winds occurred at the same location as the more intense precipitation center, along the RS coast and Laguna dos Patos regions (~ 30°S-51° W). The winds reached maximums of around 18 m/s (~ 64 $km.h^{-1}$), similar to those observed at the Tramandai meteorological station, as shown in Bartolomei et al. (2023). This cyclone was responsible for most of the positive precipitation anomaly shown for the same area previously in **Figure 3b**. In terms of extremes, from the 8 days of the cyclone lifecycle on 6 of them, the daily precipitation exceeded the P_{95}.

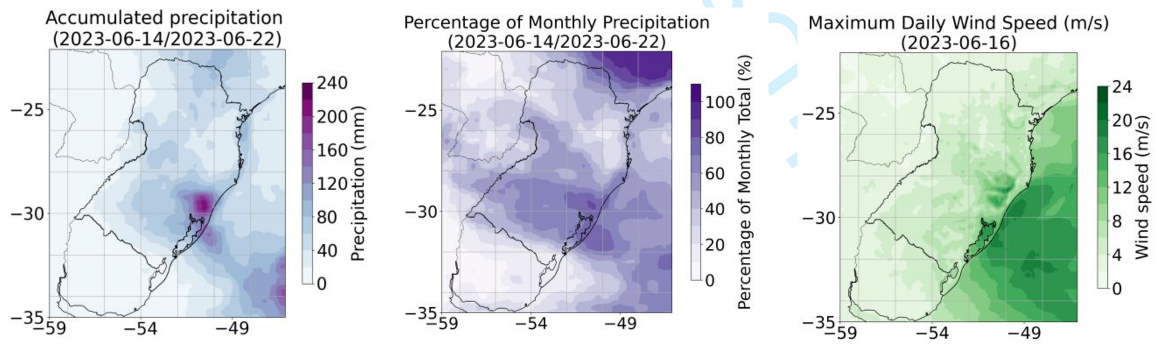
Figure 12 presents the difference between the daily precipitation on cyclone days and the P_{95} for the day where this difference was maximum. For the June of 2023 cyclone, this difference exceeded 80 $mm.day^{-1}$ in a very concentrated core in eastern of RS, which is the most populated area of the region (**Figure 12a**) The damages associated with this cyclone included 9 deaths and significant economic losses with more than 10.000 people displaced from their residences (S2iD, 2023).

Although with less intensity, July hosted another cyclone impacting South of Brazil (**Figure 11d**). It occurred between July 12 and 16th , resulting in at least 1000 people displaced from their residences (S2iD, 2023). During the event, rainfall accumulation reached approximately 120 mm (**Figure 11d**), representing ~60% of the monthly climatology for most of RS (**Figure 11e**). Maximum wind speeds associated with this cyclone reached approximately 24 $m.s^{-1}$ (86 $km.h^{-1}$) in the area covering Laguna dos Patos, the northwest, and the coast of RS (**Figure 11f**). These wind speeds are well captured by MSWX analysis and closely align with the meteorological station observation at Porto Alegre on July 13 at 12UTC, which recorded 23 $m.s^{-1}$ (Bartolomei et al., 2023). Despite the accumulated precipitation amount not being as high as for the June cyclone, for three days of the July cyclone the precipitation exceeded the P_{95}. For the day of maximum precipitation, **Figure 12b** indicates that in most parts of RS precipitation exceeds the P_{95} by more than 20 $mm.day^{-1}$.

From 2nd to 5th of September another cyclone produced great impact, with associated damages including the death of 2 people and more than 3000 displaced people from their residences (S2iD, 2023). At this time, it was considered the largest natural disaster in RS. The northwest/southeast pattern of rainfall (29ºS-33ºS and 58ºW- 48ºW) covering most parts of RS indicates precipitation associated with a cold front (**Figure 12g**). For the cyclone lifecycle, the accumulation of rainfall in excess of 200 mm.day^{-1} was observed in the central areas of RS (**Figure 12g**), which over the center-north of RS represents up to 60% of the climatology for September (**Figure 11h**). Precipitation exceeding the P_{95} was recorded on 3 days of the 4 days of the event, with the difference between maximum daily precipitation and the P_{95} occupying the center part of RS (**Figure 12c)**. For the day with maximum winds, velocities of ~10 m.s^{-1} (~36 km.h^{-1}) were observed in the region of Laguna dos Patos and the coast of RS.

For October, a cyclone occurred between the 3rd and 6th days. The accumulated precipitation for this period (**Figure 12j**) shows values around 100 mm in almost the same region as the September pattern, concentrating more in the north of RS and east of PR, but with much less intensity, since September, as an example, showed values around 200 mm for the same area. This also reflects the percentage of monthly precipitation (**Figure 11k**), which shows that around 30% to 40% of that month's precipitation occurred in this period.

a) b) c)



d) e) f)

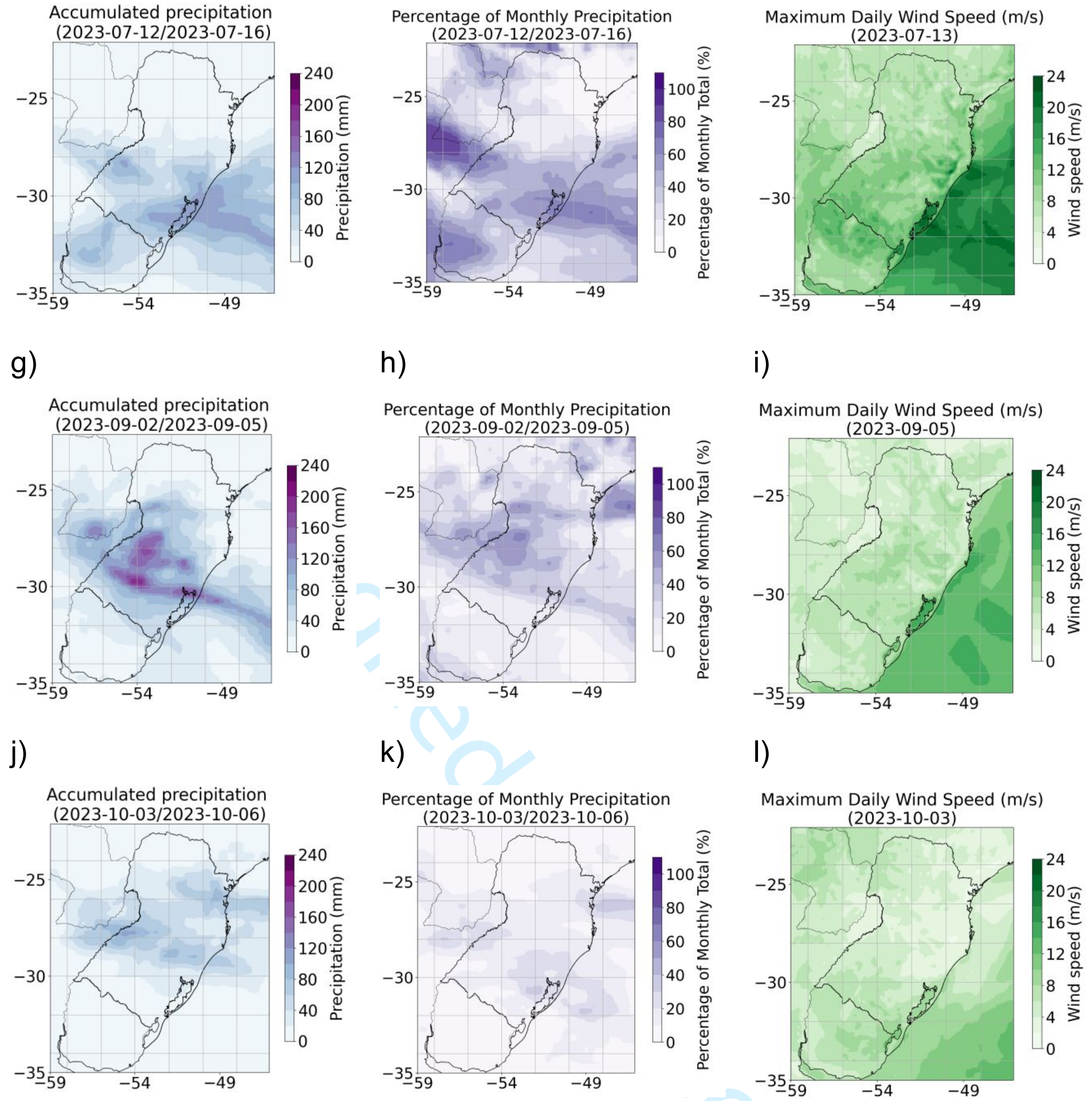


Figure 11: Accumulated precipitation (mm, left column) from MSWX reanalysis, percentage of monthly precipitation (%, center column) and maximum daily wind speed (m.s^{-1}) associated with four selected cyclones of 2023: **(a)-(b)-(c)** June 14-22, **(d)-(e)-(f)** July 12-16, **(g)-(h)-(i)** September 02-05 and **(j)-(k)-(l)** October 04-05..

a) b)

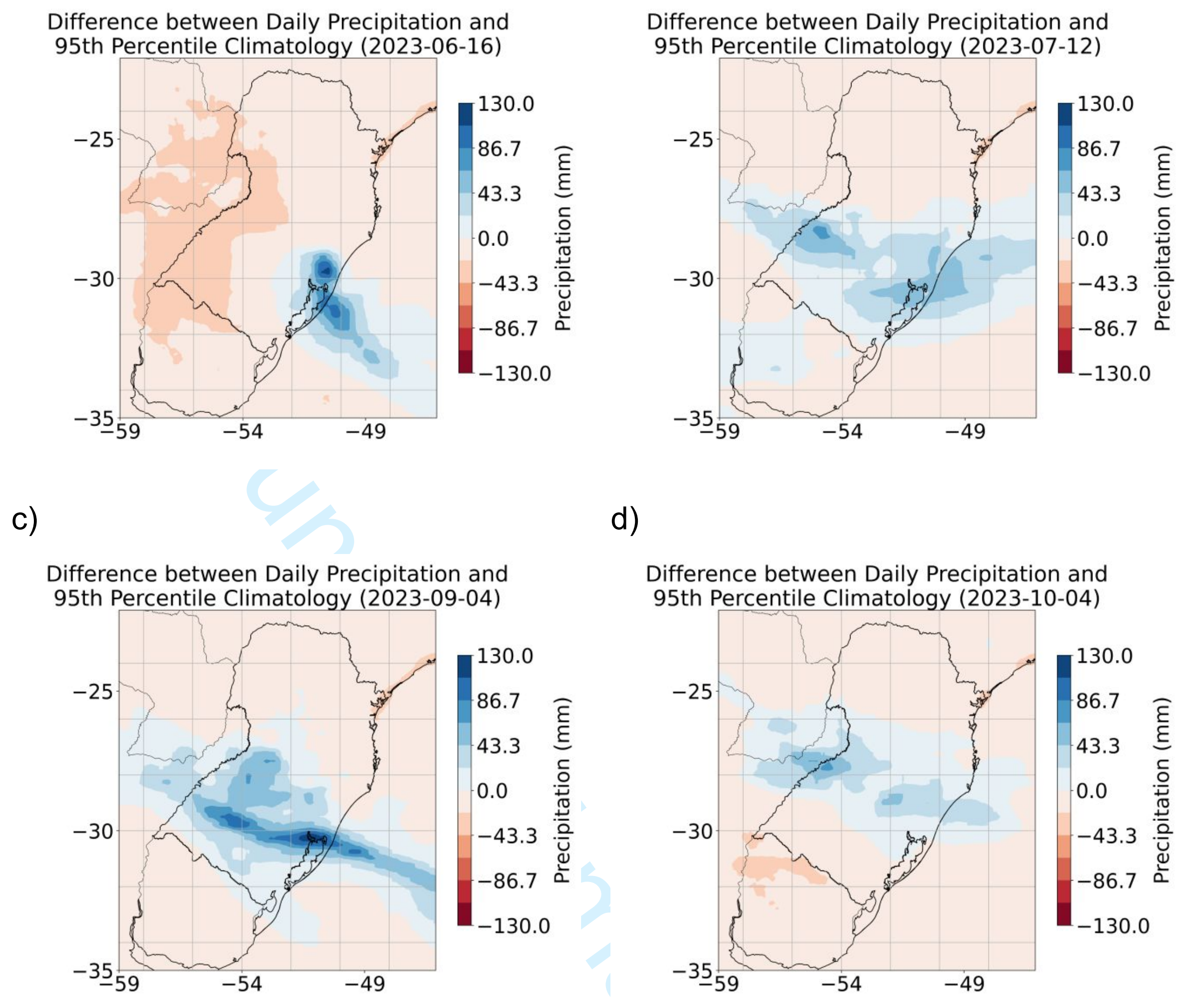


Figure 12: Day with maximum positive difference between daily precipitation and the climatological 95th percentile of daily precipitation (1991-2020) associated with the four cyclones of 2023: **(a)** June 14-22, **(b)** July 12-16, **(c)** September 02-05 and **(d)** October 04-05.

The annual mean and anomaly of cyclogenesis density for 2023 is shown in **Figure 13a**. The density indicates three main cyclogenesis cores in South Brazil and another one in Southeast Brazil (**Figure 13a**). Compared with climatology, there were in 2023 less cyclogenesis over the central part of RS, while cyclogenesis increased in the northeast and western sectors of RS (**Figure 13b**). The high positive anomaly of cyclogenesis in the extreme west and northeast of RS (**Figure 13b**) may have caused more precipitation in the east, contributing to the increased occurrence of associated cold fronts. The signal of frontal cyclones in the rainfall is indicated by the pattern of the accumulated precipitation that extends in east-west direction over South Brazil (see **Figure 11**).

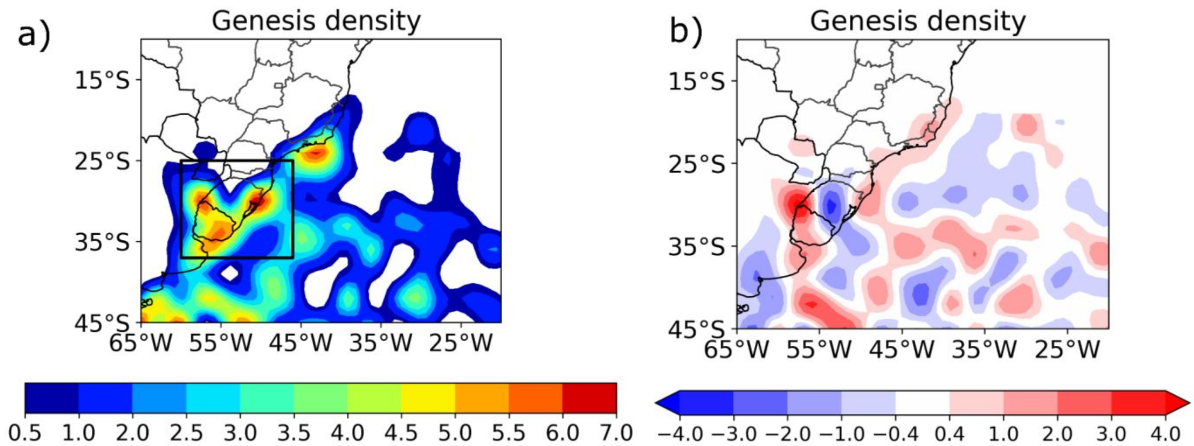


Figure. 13: Annual density of genesis: **(a)** 2023; **(b)** Annual anomaly calculated for 2023 subtracting the reference period of 1991-2020. The density unit is the number of cyclones per area (km^2) × 10^5 per year.

The predominance of the frontal precipitation pattern can also be explained from a seasonal perspective. **Figure 14** shows the seasons of winter (JJA) and spring (SON), which include the cyclones of June and September described previously, displaying a positive anomaly of density to the east and along the coast of South Brazil. This may also indicate anomalies of precipitation concentrated in eastern of that region, as well as the elongated east-west pattern for precipitation observed in the four cyclones highlighted so far.

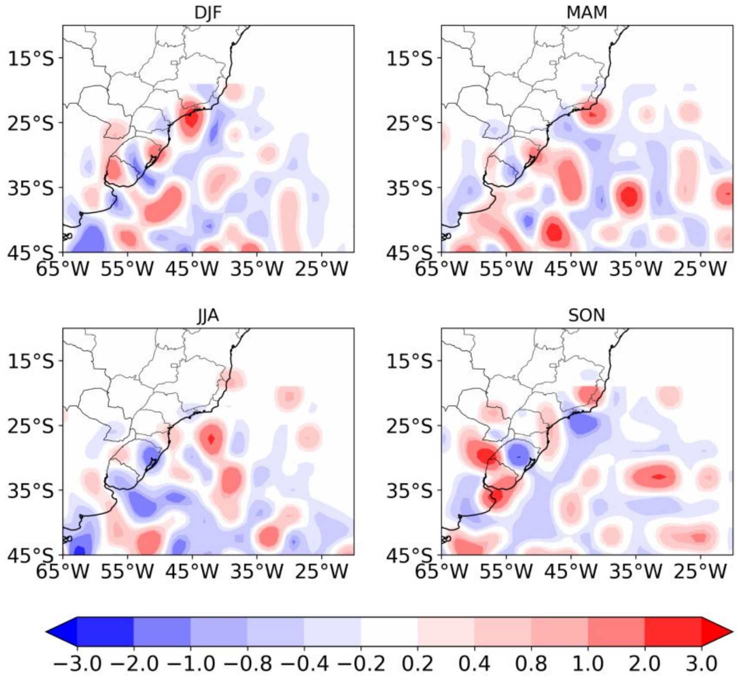


Figure 14: Seasonal anomaly of density of cyclogenesis calculated for 2023 subtracting the reference period of 1991-2020.. The density unit is the number of cyclones per area (km^2) × 10^5 per year.

When analysing the 2023 number of damage occurrences associated with extreme weather conditions, we found that the month of October had the highest number of disasters in SC, while for RS and PR August-October-November concentrate most occurrences, being November the highest for both. Although the previous months of October had the higher anomalous precipitation, there was no corresponding number of disasters for those anomalies.

This raises a question: If the precipitation associated with the cyclone of October 3-6 did not show significant amounts, which explains the overwhelming number of disasters in this month? Why October and not the other months where cyclone events caused highest precipitation amounts? It may be reasonable to assume that October's cyclone did not play a major part in causing the disasters, or at least they are not the unique part of it. From this assumption, it can be hypothesized that the precipitation in the previous months was strong enough that in October the soil became saturated in a way that it couldn't handle any more precipitation to infiltrate. Additionally, the occurrence of another cyclone, which wasn't as strong as those that occurred before, as for September's for example, made it possible for these tragedies to occur during this specific month.

3.5. The record-breaking heatwaves of Spring 2023

The record-breaking heat waves of Spring 2023 marked an unprecedented phenomenon across various regions of Brazil, as previously shown in **Figure 5** and **Figure 7**, coherent with a global trend towards extreme weather events. During this period, two significant heat spells hit a large region of Brazil and neighbouring countries, increasing the maximum temperatures by up to 10°C above the climatology in southeastern and central-western Brazil (**Figure 15**).

As detailed in the Introduction section the early-spring heat wave started in mid-September and persisted for about 10 days, contributing to the highest temperature anomaly observed in any single month in Brazil. For Southeast and Central-west Brazil, **Figure 15** shows the time series of daily anomalies in relation to climatology of 1991-2020 in the maximum air temperatures computed using various meteorological stations. Notably, warmer temperatures persisted throughout the analysed period for both Central-West and Southeast regions of Brazil. The highest temperatures occurred in the second half of September 2023, with positive anomalies exceeding 4°C for 6 consecutive days in both regions.

A subsequent heat wave episode occurred in November, characterized by exceptionally high temperatures exceeding 40°C in several locations. During this event, positive temperature anomalies exceeded 6°C for nine consecutive days in both regions (**Figure 15**). As reported by the INMET, many major cities established new record-breaking temperatures, including Cuiabá (44.2°C), Belo Horizonte (37.5°C), Manaus (40.0°C), and Rio de Janeiro (39.6°C). Araçuaí, in the state of Minas Gerais, recorded the highest temperature ever observed in Brazil (44.8°C, INMET). São Paulo (Mirante do Santana meteorological station) experienced its second-highest temperature ever recorded on November 13th and 14th (37.7°C), only 0.1°C lower than its historical record set on October 17, 2014 (INMET). The two extraordinary heat wave events ended similarly, i.e., by a sudden temperature decline associated with cold front incursions (not shown).

Comparing 2023 with previous years, the period from September to December 2023 in the Mirante de Santana meteorological station in São Paulo (not shown) presented the highest average maximum temperature of 29.5°C, with 48 (16) days exceeding the 90th (99th) percentile. These results are in agreement with previous studies (Geirinhas et al., 2018) which also observed positive trends in heat wave frequency since the 1980s, particularly in São Paulo.

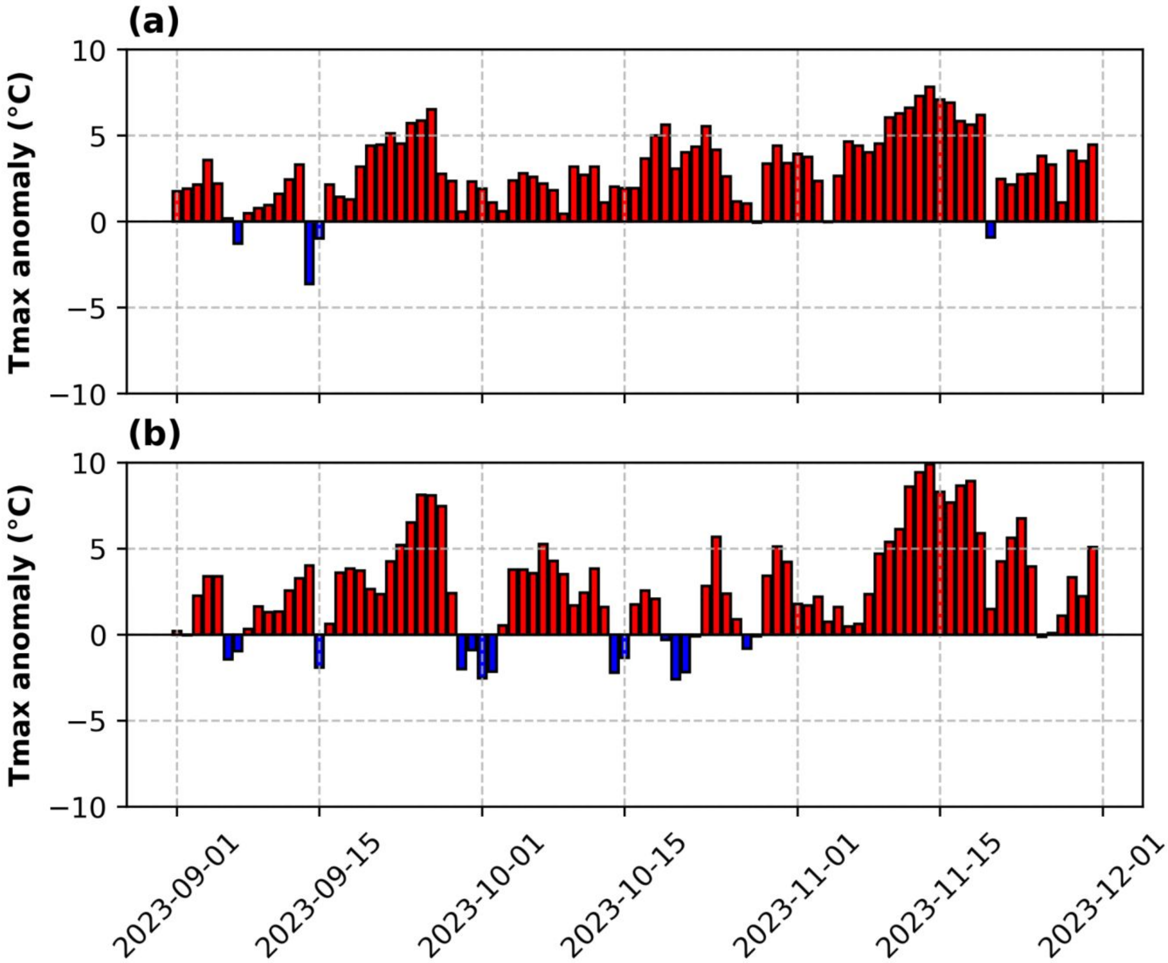


Figure 15: September 1st to November 30th, 2023 daily anomalies of maximum air temperatures for the INMET meteorological stations across the **a)** Central-West and **b)** Southeast regions of Brazil period from. Anomalies calculated from the 1991-2020 climatology.

To understand the mechanisms behind the Spring 2023 heat wave events, we analyse the typical atmospheric circulation patterns. **Figure 16** shows the large-scale features at different pressure levels for the heat wave of September 17-27, 2023 and November 11-18, 2023. Both events exhibit similar large-scale anomalous patterns. Large positive near-surface air temperature anomalies dominate central-north South America, with temperatures exceeding 5ºC in Paraguay, northern Argentina, and southern Brazil (**Figure 16a,b**). The zonal wind circulation at 200 hPa (**Figure 16e,f**) exhibits a strengthened westerly jet stream extending from the subtropical Pacific Ocean to the mid-latitude South Atlantic Ocean, with maximum winds over the La Plata basin (exceeding 50 m.s^{-1}), while weakened westerly winds over central-north South America are associated with an anticyclonic circulation. At 850 hPa, drier conditions prevail in central Brazil with negative specific humidity anomalies (**Figure 16g,h**), whereas southern Brazil exhibits increased humidity driven by northerly winds. A mid-level ridge associated with positive 500-hPa geopotential anomalies (**Figure 16c,d**) enhances subsidence in central and southeastern Brazil, suppressing precipitation and increasing temperature due to enhanced solar radiation and adiabatic compression (Gao et al. 2023). Both events also feature a Pacific-South American (PSA)-like wave train that strengthens the upper-level anticyclonic circulation over southeastern South America, as indicated by the 200-hPa stream function (**Figure 17a,b**). This wave train extends from the South Pacific to the South Atlantic Ocean, resembling the positive phase of the first PSA mode (Mo and Higgins 1998) and exhibiting a barotropic-to-baroclinic transition as it propagates equatorward.

However, some differences exist between the two heatwaves: the positive near-surface air temperature anomalies in November are of greater magnitude compared to September; anomalous upper-level easterly winds are more intense in November than in September, and southern Brazil experiences moister conditions during the November heatwave. These differences highlight variations in intensity and atmospheric dynamics despite the overall similar large-scale patterns.

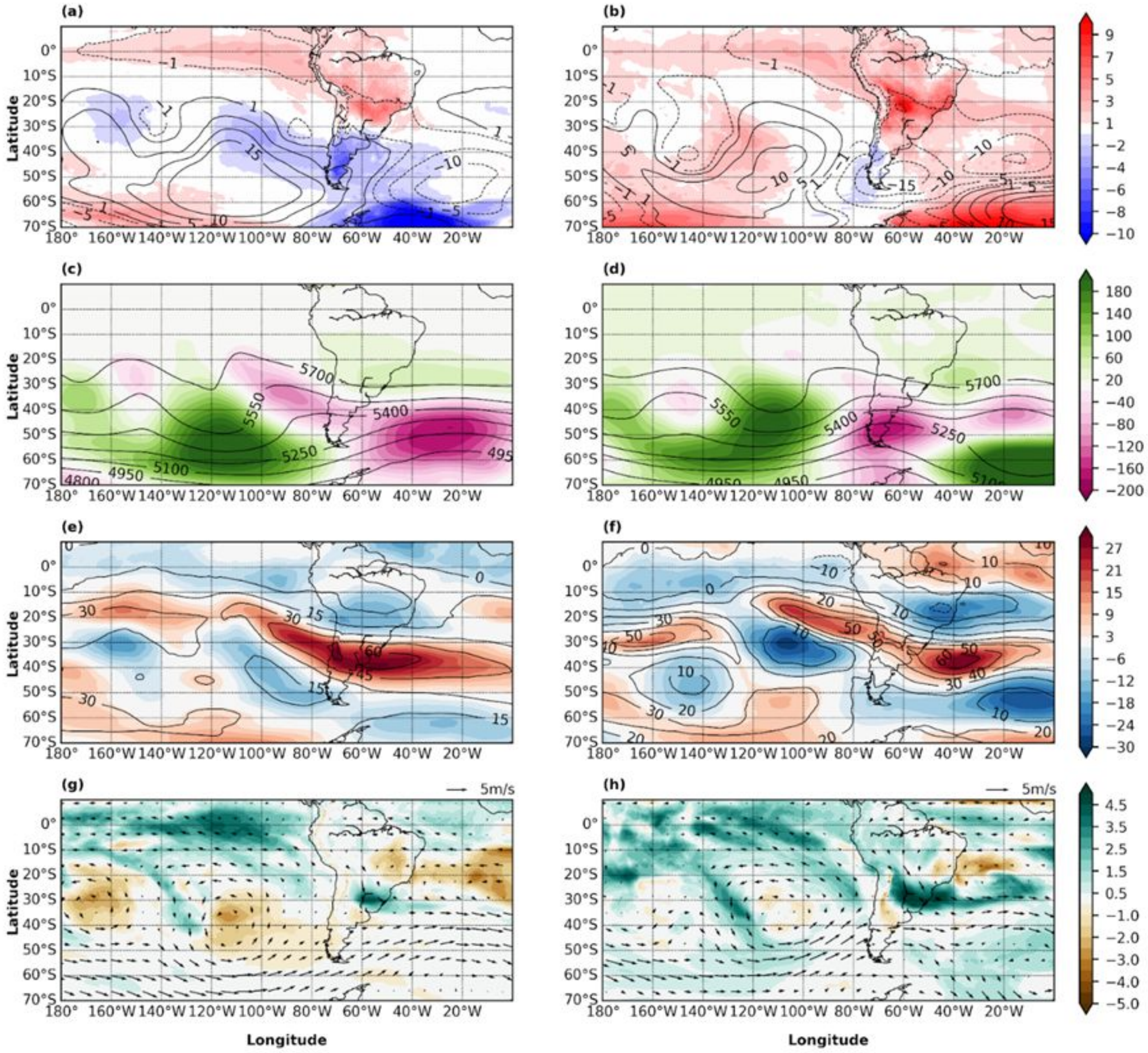


Figure 16: Synoptic conditions for heat wave episodes of **(a, c, e, g)** September 17–27, 2023 and **(b, d, f, h)** November 11–18, 2023 for the following variables: **(a, b)** anomalies of 2 m air temperature (shaded, unit: °C) and sea level pressure (contour, unit: hPa); **(c, d)** 500-hPa geopotential height (contour) and 500-hPa geopotential height anomalies (shaded, unit: mgp); **(e, f)** 200-hPa zonal wind speed (contour) and 200-hPa zonal wind speed anomalies (shaded, unit: m/s); **(g, h)** 850-hPa specific humidity anomaly (shaded, unit: g/kg) and 850-hPa horizontal wind direction (vector, unit: $m.s^{-1}$).

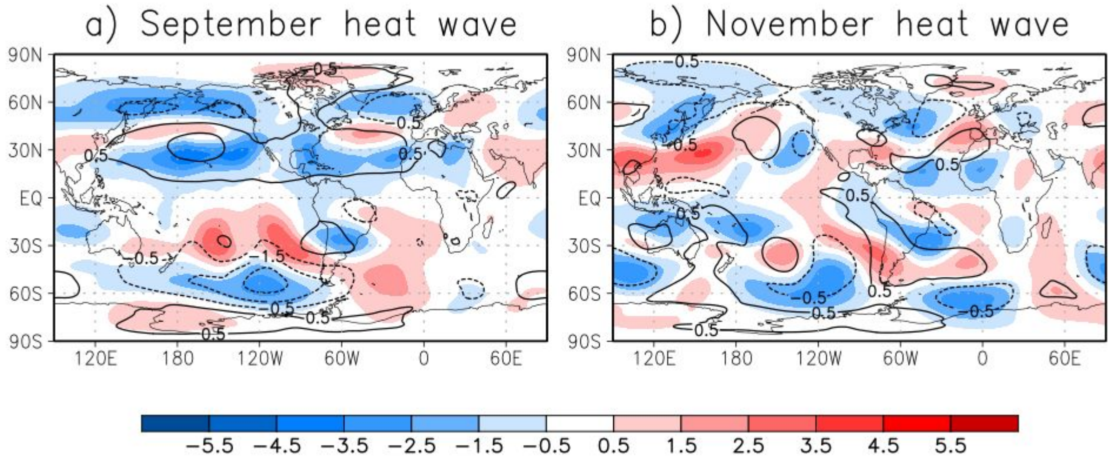


Figure 17: Stream function daily anomalies mean at 200 hPa (shaded, unit: 1 x 10^7 $m^2 \cdot s^{-1}$) and 850 hPa (contour, unit: 1 x 10^7 $m^2 \cdot s^{-1}$) for heatwave episodes of **(a)** September 17–27and **(b)** November 11–18, 2023.

4. Summary and Conclusions

This work provides a detailed analysis of the intense, and some of them extremes, climate events that impacted Brazil throughout the year 2023. This year was marked as the hottest on record in the country, with an annual mean temperature anomaly of +0.84°C relative to the 1991-2020 climatology, surpassing previous years such as 2019 and 2015, with maximum temperature breaking records in many meteorological stations. Regionally, the largest positive temperature anomalies were observed in the North, Northeast, and Southeast regions, while the South showed a more mixed signal, with periods of below and above average temperatures.

In terms of precipitation, the year was characterized by wet and dry extremes. Southern Brazil experienced a substantial increase in precipitation, often associated with cyclones that brought intense rainfall in short time intervals, accounting for a significant portion of monthly rainfall and causing natural disasters. The annual density anomalies indicate that the greater number of cyclogeneses in 2023 in the extreme southwest and northeast of RS was associated with the increased precipitation in South Brazil. This region experienced several daily precipitation extremes, primarily driven by four significant cyclones that occurred in June, July, September, and October. These events caused widespread impacts, with daily rainfall totals often exceeding the 95th climatological percentile and contributing with a great percentage of the accumulated monthly precipitation. The June cyclone, which brought up to 240 mm of rain in eastern RS, caused severe flooding and landslides, while the July event generated strong winds, which reached 24 m.s-1 over the continent, and further disruptions. The September cyclone, the most destructive of the year, resulted in over 3000 people displaced from their houses. Although the October cyclone was relatively less intense than the other three, it followed similar rainfall patterns, demonstrating the recurring influence of these systems on the region's climate and highlighting the need for effective disaster preparedness.

During the austral summer 2023, a heavy rainfall event occurred on the northern coast of the state of São Paulo, probably the event with the highest accumulation of rainfall recorded in Brazil in a single day (682.8 mm), which resulted in 65 deaths. This extreme event was associated with different dynamic and thermodynamic factors: The passage of a polar cold front, the action of a mesocyclone in the lower troposphere, a circulation similar to the South American low-level jet (from the Amazon towards the São Paulo coast), a warmer than normal subtropical South Atlantic Ocean and the orographic effect of the mountains of the Serra do Mar.

In contrast, Northern Brazil, especially the Amazon, experienced a prolonged and intense drought, with significant precipitation deficits in September, October, and November, affecting ecosystems and local communities. The prevailing large scale forcings for the austral spring 2023 Amazon drought were the El Niño phenomenon in the equatorial Pacific Ocean, and anomalous sea surface temperature warming in the tropical North Atlantic Ocean, leading to anomalous subsidence over a large portion of the Amazon due to changes in the zonal (Walker) and meridional (Hadley) circulations.

The 2023 year was also marked by climate records in various parts of the Brazil. The highest temperature on record was observed in Araçuaí (MG), where maximum temperature reached 44.8°C in November. On the São Paulo coast, the municipality of Bertioga recorded the highest 24-hour rainfall accumulation ever observed in Brazil: 683 mm between February 18 and 19. The value of 683 mm as record of highest 24-hour rainfall accumulation was almost six times greater than annual mean of total accumulated of this data (114,9 mm) from the 1981-2017 period over the mean domain on central-north coast of the São Paulo state that includes the Bertioga (Da Silva et al., 2021). Also, the 2023 record was higher than higher value found these authors of 346,6 mm occurred in January 5, March 10 and December 12 and 31, 1999. The Figure 6c from Da Silva et al. (2021) shows that during the days with daily total rainfall above 99th percentile there was anomalous intensification of the moisture and warm air transport from tropics to the central-north coast of São Paulo. The 850 hPa winds from the western quadrant of the South Atlantic Subtropical Anticyclone were deviated by the Andes together with the anomalous flow from the eastern Equatorial Pacific Ocean to Southeast Brazil. Additionally, the presence of cyclogenesis to the south of the central-north coast of São Paulo was observed.

Heatwaves were a significant phenomenon throughout the year, especially during the austral spring. The WSDI index indicated that some stations in the North and Northeast recorded over 100 days of heatwaves, with unprecedented duration and magnitude. Southeastern and Central-West Brazil experienced two intense heat waves due to a synoptic pattern characterized by an anomalous persistent mid-tropospheric ridge over central and Southeastern Brazil. This system trapped warm air leading to prolonged high temperatures (positive temperature anomalies up to 4°C) in large areas of Southeastern Brazil. The situation might have been related to the El Niño conditions, which typically PSA-like wave train propagating from the south Pacific to the South Atlantic.

In conclusion, 2023 was a year of extreme climate events in Brazil, reflecting global warming trends and highlighting the need for mitigation and adaptation actions to address climate change and its increasingly severe impacts on the country. The growing intensity and frequency of extreme climate events, driven by global warming, places Brazil in a position of urgency to strengthen response strategies, aiming to reduce vulnerabilities and protect both natural resources and the communities directly affected.

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